CRWR Online Report 08-05

Texas Integrated Drought Information System

A Prototype of the Trinity River Basin

by

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May 2008

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Acknowledgements

The author would like to thank Dr. David Maidment for his teaching, guidance and support throughout this project. Additionally, the author would like to thank faculty and students of the Center for Research in Water Resources for their support and assistance.

The author would also like to thank the Texas Natural Resources Information System for sponsoring this research, and for guiding her work.

May 2008

Abstract

A Texas Integrated Drought Information System Prototype

For the Trinity River Basin

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In order to improve drought mitigation, the Texas Water Development Board (TWDB) initiated a research project to design a prototype of an Integrated Drought Information System (IDIS) for Texas. The IDIS is a tool for drought monitoring that functions by incorporating several sources of disparate drought information. The goals of the IDIS are to create an information system that will allow decision makers, researchers and the general public access and information about drought conditions. This report describes the ideas, framework and process used in developing the IDIS prototype for the Trinity River Basin, in Texas.

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Chapter 1. Introduction

The word "drought" can conjure up many different ideas. Simply defined, drought results from a deficiency in precipitation for an extended period of time. Drought is a naturally reoccurring hazard, which varies by geographic region. Droughts have always plagued societies. All inhabited land is subject to drought. Texas is far from an exception. Droughts occur regularly in the state, impacting the industries, economies and societies of the state. Despite advancements in technology, geosciences and hydrologic engineering, droughts continue to ravage communities. However, today new concepts and approaches are being developed to mitigate drought. Leading the way in drought mitigation is the development of integrated drought information systems.

Integrated information systems are useful because they are able to incorporate information from many resources. Due to the complexities of drought many resources of climate data and hydrologic data must be combined to create a realistic and comprehensive drought monitor. Scientists have known this for a long time. To overcome this problem drought experts have developed an array of drought indices to describe droughts. However, these indices are often complex and too scientifically cumbersome for non-scientist and non-engineers. Until recently the technology has not existed to create a true integrated system for drought. Advancements in data collection, data management, server technology and the internet have enabled the idea of a drought integrated information system a reality. Not only does this technology advance drought research, but will also inform decision makers and the general public as to drought conditions.

1.1 Integrated Drought Information System (IDIS) Definition

An integrated drought information system is a computer based system for providing drought related information. The system is hosted and served from one location; however it integrates information related to drought from several different networks. By integrating disparate drought information, it is able to create a more complete picture of drought.

To better combat drought in Texas the Texas Department of Natural Resource Information Systems (TNRIS) requested the Center for Research in Water Resources (CRWR) at the University of Texas – Austin (UT) to develop an Integrated Drought Information System prototype. The prototype was commissioned for the Trinity River Basin, one of the largest and most populated basins in the state. The software being used is ArcGIS, a product of the Environmental Systems Research Institute, Inc. (ESRI).

The purpose of the prototype IDIS is to create a system to aid decision makers, the public and researchers. To meet the disparate information needs of these diverse groups the IDIS incorporates many different types and forms of information. Additionally, to truly describe drought, climate data must be combined with hydrologic data. The services that the IDIS incorporates are drought indices, hydrologic data, climate related data, drought education and drought links. Through the IDIS, users can obtain information about recreation access points, reservoir levels, stream flow information, drought index, crop moisture levels, historical precipitation, soil moisture, potential evaporation, and temperature, and reported drought impacts. This data is made available through the Geographic Information System (GIS) component of the project. In addition, the IDIS serves as an educational portal. The IDIS website provides links to educational material and other informative drought related websites.

The IDIS project uses an amalgamation of information resources. The drought information accessed for the purpose of the IDIS comes from the United States Geologic Survey (USGS) National Water Information System (NWIS), National Oceanic Atmospheric Administration (NOAA) National Center for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR), the NOAA Climate Prediction Center (CPC) Crop Moisture Index (CMI), the National Drought Mitigation Center's (NDMC) U.S. Drought Monitor and Drought Impact Reporter. The basemap for the project is created from the National Hydrography Dataset Plus (NHDPlus) and the TNRIS Strategic Mapping Program (StratMap).

1.2 Types of Drought Information

The IDIS is designed in an attempt to overcome some of the ambiguities in drought models. It is unique because incorporates information from so many disparate types of drought information resources. The IDIS is composed of four main components: drought education, links to drought resources, current reservoir elevation information, and a geographic drought information system. Of these four components the geographic information system is the most complex. This system defines the IDIS, as it integrates drought and geographic data from many sources to describe drought conditions as they change in relation to time.

The IDIS is composed of features that can be broken in to two groups: static and space-time. Static features do not change. The only data they possess is data that describes the feature. They make up the Hydro Basemap. The Hydro Basemap is the backdrop geographic to the whole system. It serves as a reference for users. The features of the basemap don’t actually contain any drought information; however, their existence gives users a base to interpret drought data. That base may be physical, political, or regional. The features included in the Hydro Basemap are typically: towns, cities, counties (however, counties is not one of the Hydro Basemap layers for the prototype described in this paper, this will be explained further in chapter 4), state boundaries, roads, interstates, water bodies, flowlines, drainage basins and river basins.

The space-time layers of the system are the dynamic layers. These layers contain features that have data attached to them changes through time. The feature geometries may be static through time or change with time. They may be feature layers or a catalog of rasters. The important aspect is that each is associated with time series data. The idea of these layers can be described in Figure 1.1. This figure shows the relationship between geographic data and variable values in relation to time series. As can be seen through the model in Figure 1.1, data change features are associated with variables that change through time. Time series are required to create a full hydrologic model.

Hydrology changes with time and therefore, time must be incorporated into an accurate hydrologic model. Space-time layers may include: stream gauges, reservoirs, and regions (for the purpose of this paper, counties and a raster catalog of reservoir depths are included). [8]

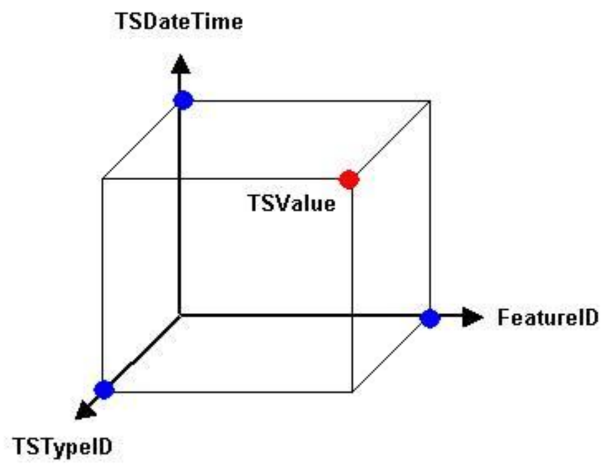


Figure 1.1: Time series values are a function of features, time and variable type. [8]

Figure 1.2 describes the different types of layers used in the IDIS prototype project described by this paper. The map to the absolute left shows the study region for the prototype. The rows of the slanted maps show the feature layers of the project. The flat layers (to the left) represent static layers of the project. They are the Hydro Basemap. The feature layers that appear to have depth (to the absolute right) represent the space-time layers of the project. They have data attached to them that makes them dynamic through time.

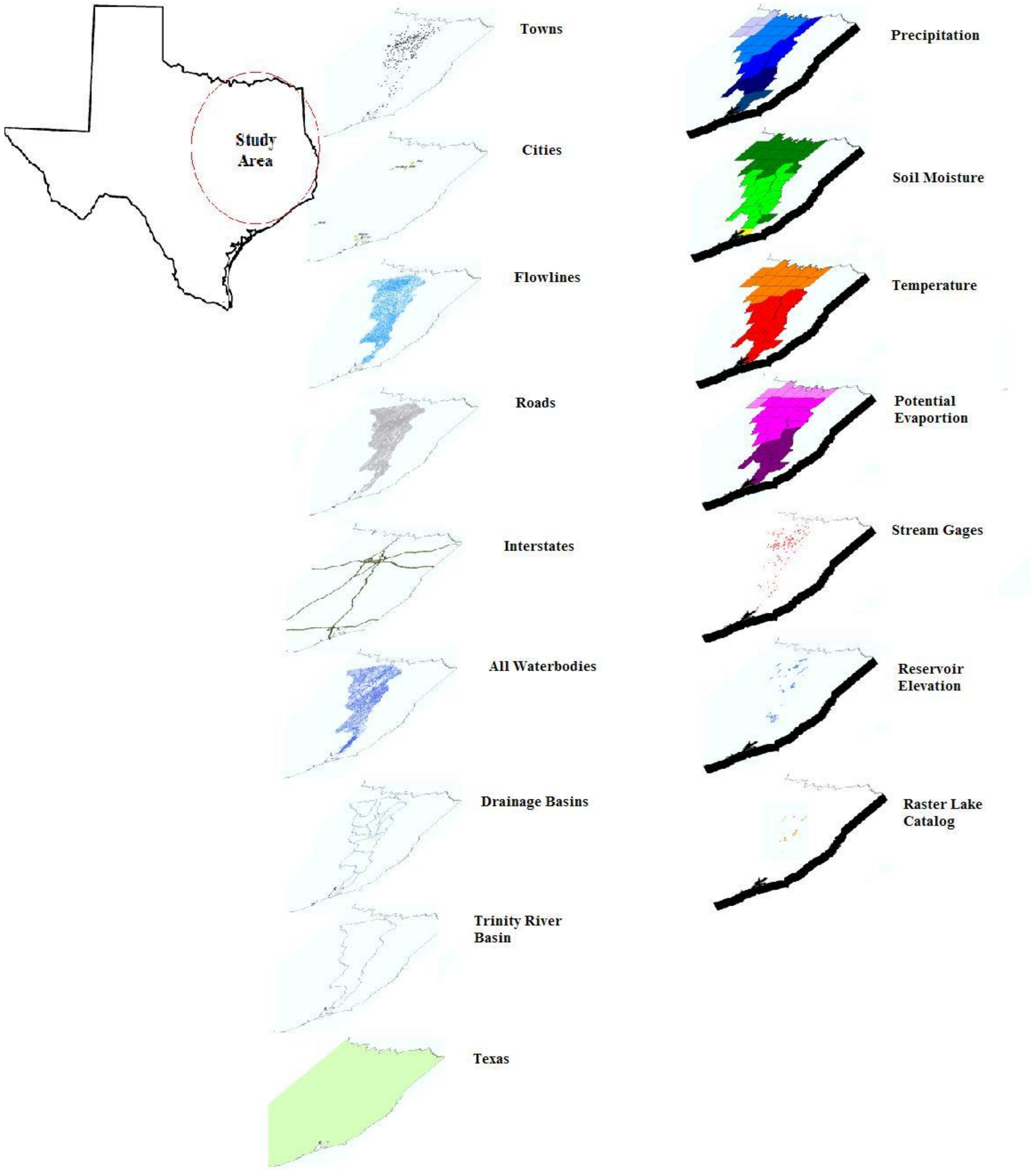


Figure 1.2: The IDIS prototype project, for the Trinity River Basin, uses both static feature layers and feature layers that are dynamic through time.

1.3 IDIS Functions

The IDIS functions as a public information system for drought. As mentioned earlier in this section, there are four main types of information accessible to the public: drought links, drought education, reservoir elevation levels, and a geographic drought data information system. The first three of these types are simple forms of information. The users can obtain these automatically through accessing the IDIS website. The drought education portion of the project is available as a document. The document is designed to explain and define drought and its many variables to the non-scientist. The drought links available on the IDIS website are links to on-going national drought information projects. The drought links include: the US Drought Monitor, the Drought Impact Reporter, the Crop Moisture Index and the National Integrated Drought Information System (NIDIS). The reservoir elevation table is a table of reservoirs within the Trinity River Basin that are monitored by the USGS NWIS. Using scheduled tasks, the reservoir elevations are updated daily with the previous day's average elevation, as reported by NWIS. The geographic drought data information component of the IDIS is more complex has several functions within it. This report will delve greater into the science behind these functions. However, a summary of these functions are summarized here:

Drought Related Indices - There are several drought indices produced in the US by government organizations. Some of these include the US Drought Monitor, the Drought Impact Reporter and the Crop Moisture Index. The IDIS uses Windows Mapping Service (WMS) files to map updated versions of these indices for users to view in relation to other drought related data.

Hydrologic Data– Hydrologic data for surface water is obtained from the USGS NWIS. The data used describes the reservoirs and stream flow of the Trinity River Basin. The data is retrieved via web services, and is available for the user to download as a table or view the data as a graph. The data is attached to stream gauge features and reservoirs by a HydroCode, which matches the USGS identifier.

Climate Data– Climate data is available for four variables: soil moisture, temperature, potential evaporation, potential evaporation, subsurface runoff and non-infiltrating surface runoff, and precipitation. These variables were chosen because of their relationship to and impact on drought. The data to support this information is obtained from the NARR (more information about NARR can be found in section 3.4). The IDIS server hosts a catalog of the NARR data, which extends from 1979 to the present. The data is updated monthly, with the previous month's average values using scheduled tasks. The data is attached to the Trinity River Basin counties feature layer. Users can obtain the data as a downloadable table or view the data as a graph for specified variables and time periods.

1.4 Report Objectives

The objectives of this report are to describe the format of a Texas IDIS prototype and the method for its creation. This paper predominately focuses on the technical aspects of the creating this system. The goals of this paper are to:

- give a full description of drought classification and its impact on drought planning
- Explain the role of IDIS in the Texas's drought plan for drought mitigation
- Describe the framework for an IDIS for Texas such as methods of data integration and available data resources
- Detail the IDIS prototype in the Trinity River Basin
- Show the steps taken to develop the IDIS prototype
- Make recommendations for future efforts in developing an IDIS for the state of Texas

Chapter 2. Literature and Technology Review

To establish an IDIS, it is important to understand the impacts, implications and policies surrounding drought. The IDIS is a tool for drought mitigation that functions as a public information source. Therefore, it is important to understand drought, the drought cycle, drought's relationship to the environment and droughts relationship to society. For the IDIS to be a useful tool it must provide users, such as decision makers, with the appropriate tools to manage a drought. Therefore the tool must be adaptive intellectually to an array of scientific backgrounds. In creating a tool such as this, first the history of drought must be studied; as well as policy for managing and mitigating drought events. Finally, it is important understand the technology that has been developed for creating an integrated information system such as this. This section reviews the existing literature and technology of these topics.

2.1 Drought Classification

Before understanding the ideas behind creating a drought information system it is import to have a clear definition of drought. The word "drought" has different meanings. Tannehill gave a good description of the word in his book, Drought and Its Causes and Effects (1947) [1]

> *"We have no good definition of drought. We may say truthfully that we scarcely know a drought when we see one. We welcome the first clear day after a rainy spell. Rainless days continue for a time and we are pleased to have a long spell of such fine weather. It keeps on and we are a little worried. A few days more and we are really in trouble. The first rainless day in a spell of fine weather contributes as much to the drought as the last, but no one knows how serious it will be until the last dry day is gone*

> *and the rains have come again... we are not sure about it until the crops have withered and died."*

The most basic definition of drought is a deficiency in precipitation for an extended period of time. [2] It's difficult to establish when a drought is truly beginning. When do a string of sunny days turn into a drought? The question can be answered differently according to the type of drought that is being analyzed. [3] The range of definitions for droughts can be defined by rainfall amounts, vegetation conditions, agricultural productivity, soil moisture, levels in reservoirs, stream flow or economic impacts. It results in water shortages for residents, farmers, industry, and environments. [1] Drought is a natural reoccurring hazard of nature, which varies by region. There are not a standard number of sunny days that define drought; drought must be defined relative to "normal" water balance for that region. [3]

The water balance depends on the water cycle described in Figure 2.1. The water cycle includes all of the hydrologic processes; such as precipitation, evaporation, evapotranspiration, streamflow and runoff. The water cycle interacts with the land surface and to the atmospheric cycle to drive climate and hydrologic processes for a region. Climate regions differ by water cycle due to geography, geology, and land cover. Water cycles may be more or less variable and differ by volume.

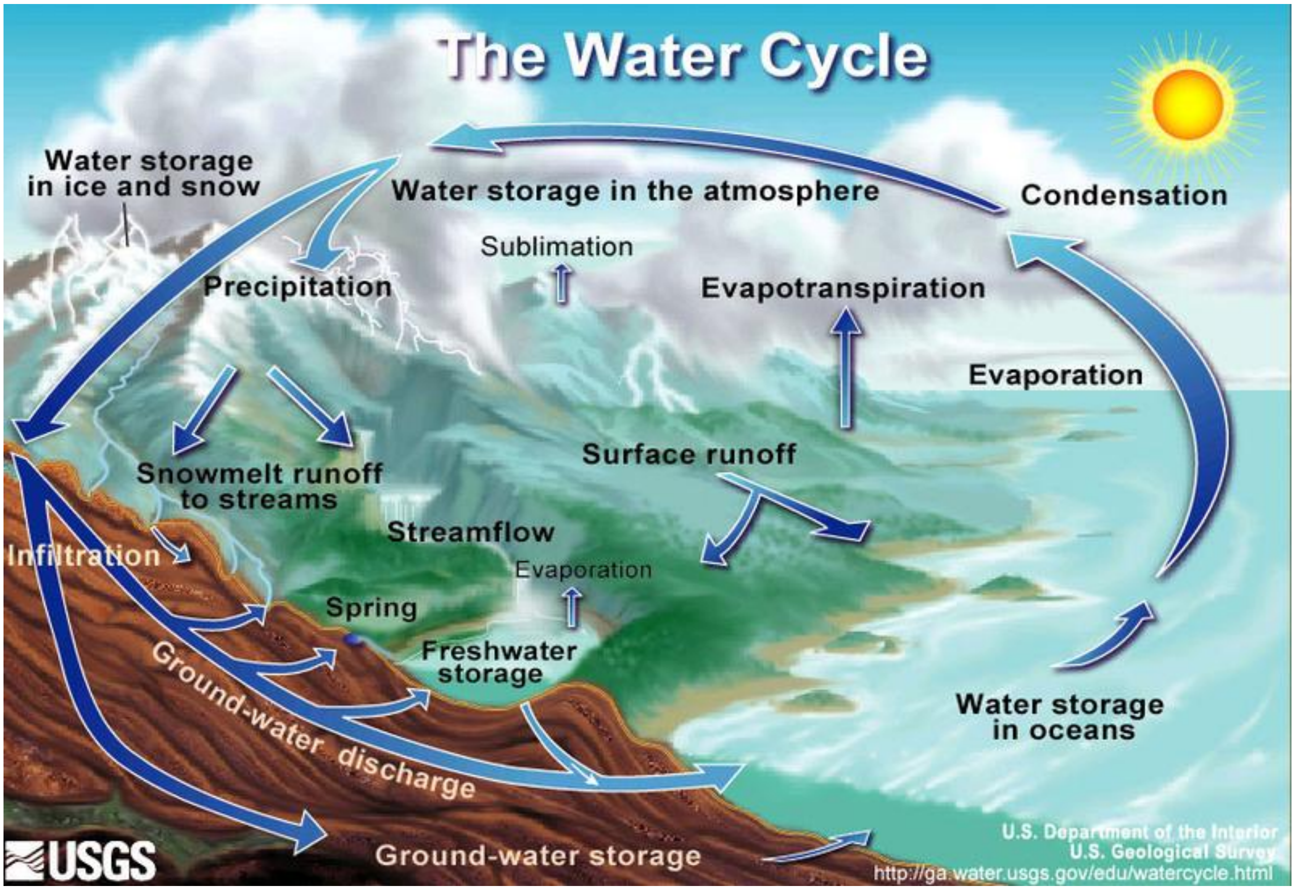


Figure 2.1: The water cycle is the cycle of water through the environment. [4]

There are three main types of drought: meteorological, agricultural, and hydrological. The first of these to occur is the meteorological drought. This occurs directly from climate variation, a decrease in precipitation. The results of the meteorological drought lead to an agricultural drought. A decrease in the availability of water causes soil moisture to decrease and vegetation stress to increase. This in turn leads to a hydrological drought. During a hydrological drought the effects of drought can be seen on the surface water. These three types of drought are discussed further below. [3]

1. Meteorological drought is brought about when there is a prolonged period with less than average precipitation. Meteorological drought usually precedes the other kinds of drought.

2. Agricultural droughts are droughts that affect crop production or the ecology of the range. This condition can also arise independently from any change in precipitation levels when soil conditions and erosion triggered by poorly planned agricultural endeavors cause a shortfall in water available to the crops. However, in a traditional drought, it is caused by an extended period of below average precipitation.
3. Hydrological drought is brought about when the water reserves available in sources such as aquifers, lakes and reservoirs falls below the statistical average. Like an agricultural drought, this can be triggered by more than just a loss of rainfall.

The way these types of droughts occur can be seen below. Figure 2.2 shows the process in which the types of droughts occur and what occurs during these droughts in relation to time. It is important to note that meteorological, agricultural and hydrological droughts all have economic, social, and industrial impacts. [3]

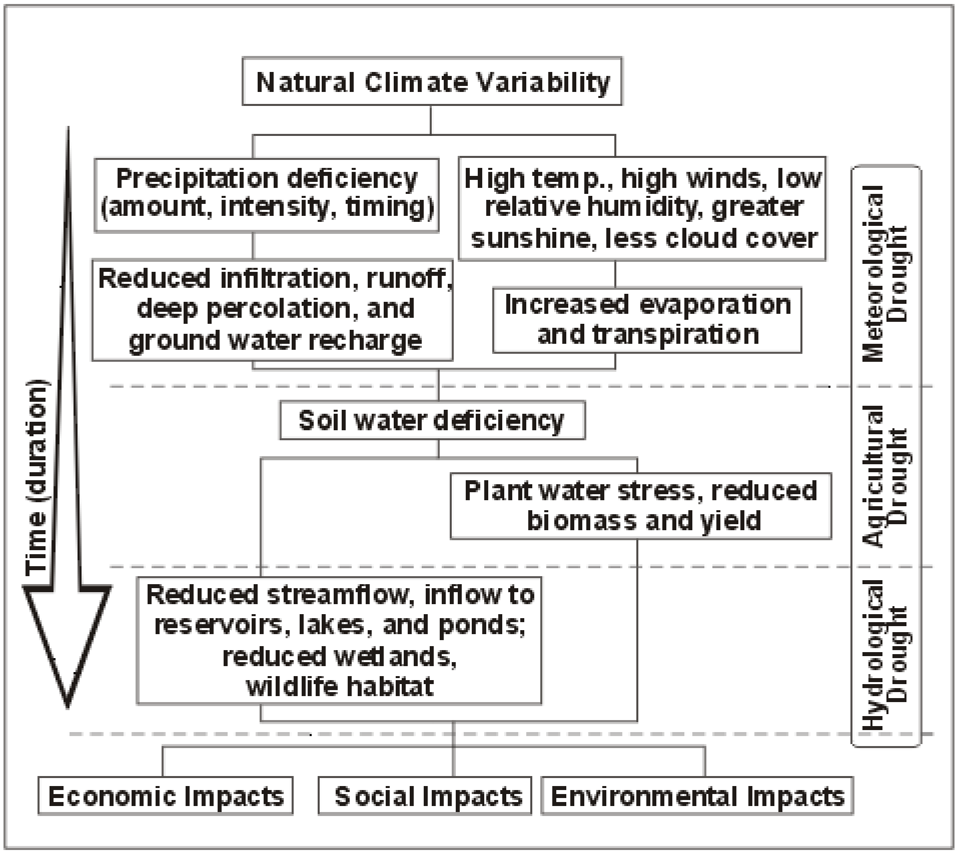


Figure 2.2: There are three types of drought: meteorological, agricultural, and hydrological. [3]

Droughts are very costly disasters. The drought of 1988 is the most costly weather event in the history of the United States. The 1988 drought cost approximately $40 billion, predominately in losses in the corn and soybean agriculture industries. [5] In a 1995 report issued by the US Federal Emergency Management Agency (FEMA) the annual loss in the US due to drought is $6-8 billion. Drought occurs somewhere in the US every year, and approximately twelve percent of the US experiences severe drought at any given time (excluding Hawaii and Alaska). The state of Texas has been subject to several major droughts through the history of the United States. In both 1996 and 1998 Texas lost nearly $5 billion to drought. These losses were mainly due to fires and agricultural failures. [6]

However, the effects of a drought are more than economic. The impacts of drought can be divided in to three main groups: economic, social and environmental. Some examples of these types of impacts are listed in Table 2.1. [3]

Table 2.1: Types of Drought Impacts [3]

Type of Impact	Examples of Impacts
Economic	Costs and losses to agricultural and livestock producers, loss of fishery productions, decrease in land prices, loss in industries/manufacturers, unemployment, strain on financial institutions (foreclosures, credit risk and capital shortfalls), government revenue loss, decrease in recreational businesses and tourism, increase in energy demand, reduction in energy supply, cost of water transport/transfer and supplemental water resources, increase in food prices, and increase in food importation
Social	Rural population loss, health, increased conflicts, reduced quality of life, public dissatisfaction with government drought response increased data/information needs, coordination of dissemination activities, recognition of institutional restraints on water use
Environmental	Damage to animal species and plant communities, increase in the number of wild fires, wind/water erosion of soils, poor air quality, decrease in visual and landscape quality, lower water body levels, reduced flow from springs, reduced stream flow, loss of wetlands, salinity fluctuations in bays and estuaries, groundwater depletion, and negative effects on water quality.

At this time droughts cannot be fully predicted. In fact, it is difficult to tell when a drought is beginning (or if it is a spell of sunny weather). In some regions drought can be defined by few days without rain (rain forest areas); while, other locations can go months without rain and still not be in true drought (dessert areas). [1] It is also difficult to know when a drought is ending. Some droughts (like the 1950s drought of Texas) are broken up by a wet spell. [5] Wet spells sometimes occur during droughts, but do not last long enough for the area to recover from drought. Although scientists cannot fully predict droughts, they have identified several variables that affect drought to get an idea of when and where droughts will occur. [7] The variables that are studied to predict drought are global weather patterns, high pressure, the tropical outlook, and the temperate zone outlook. [3]

There is still much debate over why droughts occur. Droughts are reoccurring events that are largely the result of fluctuations in climate. They are caused by a decrease in the amount of water in a water balance for a given region. There are so many variables that are believed to contribute to the onset of drought that science has yet to isolate the exact causes of drought. However, science has been able to identify several factors that induce drought. Some of the factors National Drought Mitigation Center (NDMC) scientists study are listed below. [3]

Global Weather Patterns

A great deal of research has been conducted in recent years on the role of interacting systems, or teleconnections, in explaining regional and even global patterns of climatic variability. These patterns tend to recur periodically with enough frequency and with similar characteristics over a sufficient length of time that they offer opportunities to improve our ability for long-range climate prediction, particularly in the tropics. One such teleconnection is the El Niño/Southern Oscillation (ENSO). Figure 1.3 shows an ENSO as it moves across the Pacific Ocean. This image is based on satellite data from the NOAA National Environmental Satellite, Data Information Service (NESDIS). The colors reflect sea surface temperature. The warmer area (the redder area) is the El Nino. [3]

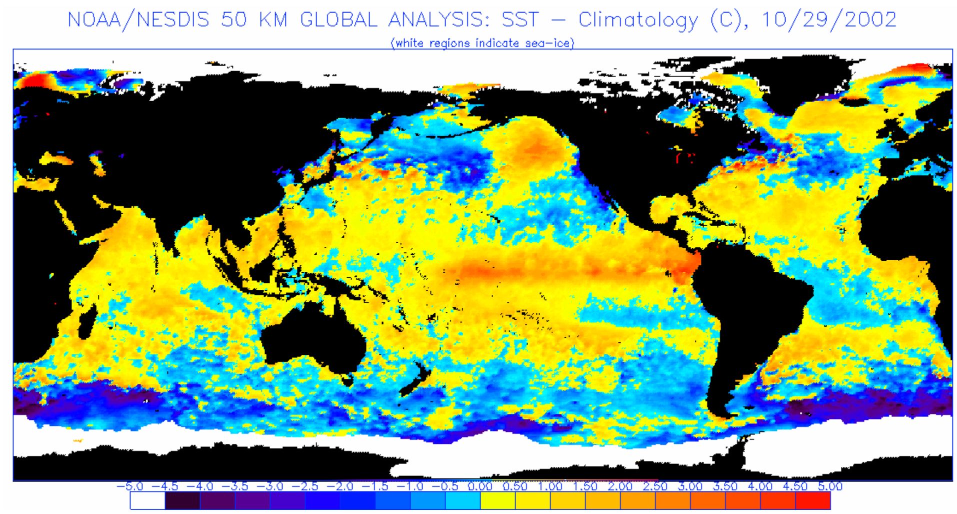


Figure 2.3: A satellite image produced by NOAA to show the impacts of El Nino on 2002 on global sea surface temperature. [6]

High Pressure

One immediate cause of drought is the predominant sinking motion of air (subsidence) that results in compressional warming or high pressure, which inhibits cloud formation and results in lower relative humidity and less precipitation. Regions under the influence of semi-permanent high pressure during all or a major portion of the year are usually deserts, such as the Sahara and Kalahari deserts of Africa and the Gobi Desert of Asia. Most climatic regions experience varying degrees of dominance by high pressure, often depending on the season. Prolonged droughts occur when large-scale anomalies in atmospheric circulation patterns persist for months or seasons (or longer). The extreme drought that affected the United States and Canada during 1988 resulted from the persistence of a large-scale atmospheric circulation anomaly. [3]

The Tropical Outlook

In the tropics, for example, meteorologists have made significant advances in understanding the climate system. Specifically, it is now known that a major portion of the atmospheric variability that occurs on time scales of months to several years is associated with variations in tropical sea surface temperatures.

The Tropical Ocean Global Atmosphere (TOGA) project has produced results that suggest that it may now be possible to predict certain climatic conditions associated with ENSO events more than a year in advance. For those regions whose climate is greatly influenced by ENSO events, TOGA project results may help produce more reliable meteorological forecasts that can reduce risks in those economic sectors most sensitive to climate variability and, particularly, extreme events such as drought. [3]

The Temperate Zone Outlook

In the extratropical regions, current long-range forecasts are of very limited reliability. The ability that does exist is primarily the result of empirical and statistical relationships. In the tropics, empirical relationships have been demonstrated to exist between precipitation and ENSO events, but few such relationships have been confirmed above 30 degrees north latitude. Meteorologists do not believe that reliable forecasts are attainable for all regions a season or more in advance. One reason for this is the presence of additional oceanic atmospheric oscillations, such as the North Atlantic Oscillation (NAO). [3]

Too Many Variables

Scientists don’t know how to predict drought a month or more in advance for most locations. Predicting drought depends on the ability to forecast two fundamental meteorological surface parameters, precipitation and temperature. From the historical record we know that climate is inherently variable. We also know that anomalies of precipitation and temperature may last from several months to several decades. How long they last depends on air–sea interactions, soil moisture and land surface processes, topography, internal dynamics, and the accumulated influence of dynamically unstable synoptic weather systems at the global scale. [3]

The potential for improved drought predictions in the near future differs by region, season, and climatic regime.

The multiple dimensions and unpredictability of drought makes it necessary to incorporate several types of disparate data to draw an accurate picture of drought. This project does not be using all of the resources mentioned above, because the goal of this project is not to predict drought, but to model drought as it has occurred and is currently occurring.

2.2 Drought in the US

Drought is a naturally occurring aspect in all regions of the world, although a drought may be defined differently region to region. For many regions in the world climate change is altering the nature of drought. Some of these changes can be seen in the US. According to the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report, changes in temperature, precipitation and humidity have been seen across the US. According to the report, like much of the rest of the high latitudes, the United States has experienced a general increase in precipitation over the past century. As the temperature increases the air is able to hold more moisture and evaporation increases, leading to more precipitation. This has been the case for the eastern United States, but not the western. The western United States has actually experienced a decrease in the amount of annual precipitation. Not only has the amount of precipitation changed in the United States, but the characteristics have also changed. Major precipitation events, such as floods, are more common. And, rainfall has shown more seasonal trends. These attributes balance each other out, making it difficult to assess the drying/wetting condition of the United States as a whole. [9] This can be seen in the number of drought events that has occurred over the past century. The percent of the US in serve drought for a given year through the 20th century can be seen in Figure 2.4. [6]

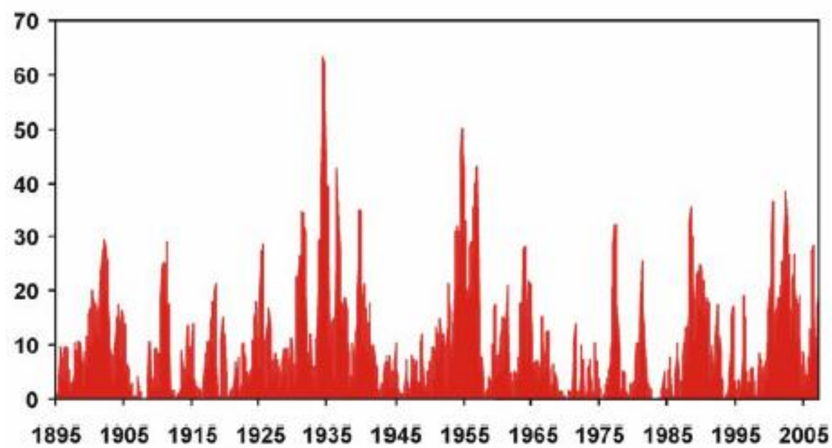


Figure 2.4: This graph shows the percent of the US in severe drought since 1895 to present.[6]

Because of the vast size of the US, the intensity of drought varies greatly across the country. The Palmer Drought Severity Index (PDSI) is a useful tool for this type of analysis. Figure 2.5 shows how long regions with in the United States have been experiencing drought through analyzing the PDSI. In the eastern and far west states have had a relatively low amount of drought in the past century. However, the Midwest and southwest have experienced more intense drought. There are several theories concerning the influences for the dryness in the central states. One impact is the ENSO cycle. As temperature rises, weather events, such as El Ninos, become more extreme due to a rise in sea surface temperature. The ENSO cycle has clear impacts on the precipitation with in the US, particularly in the south central and southwest states. Therefore, ENSO may be a contributor to the extended dry periods. Another aggravator of the dry periods is the increase in evaporation. This rise has a more prominent and lasting impact in regions of the US already subject to water scarcity. [6]

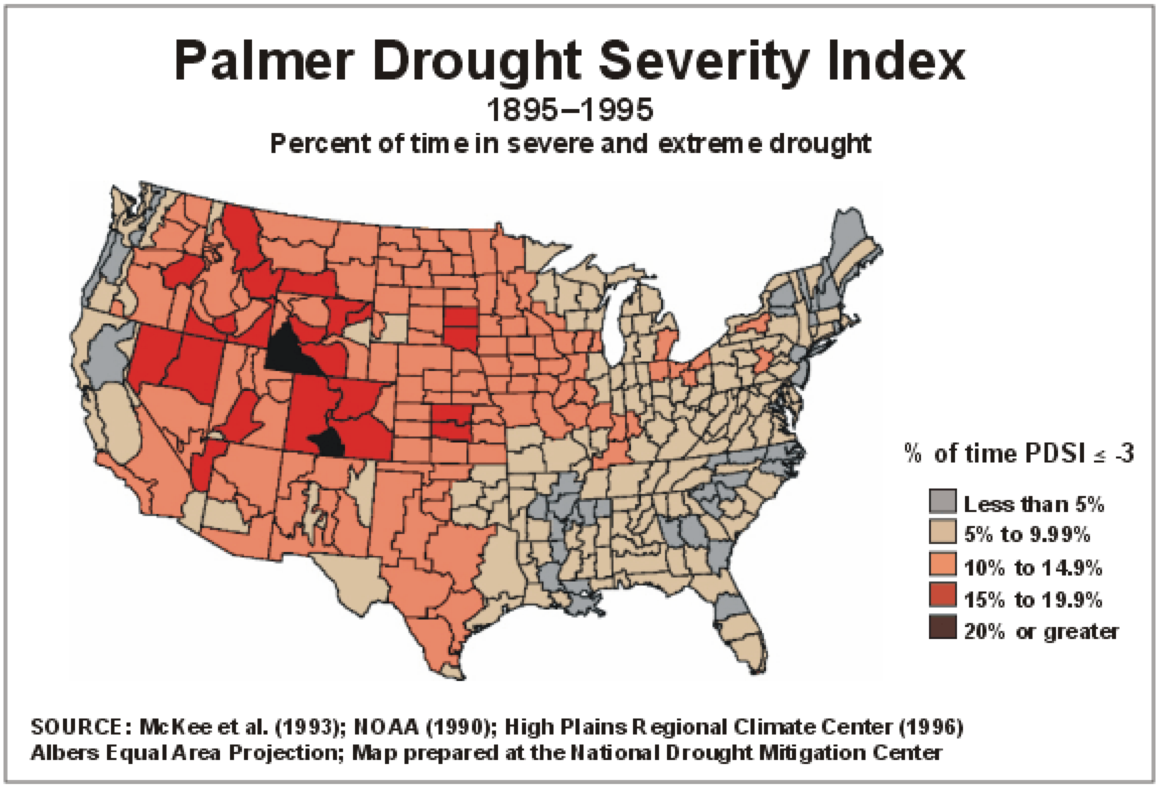


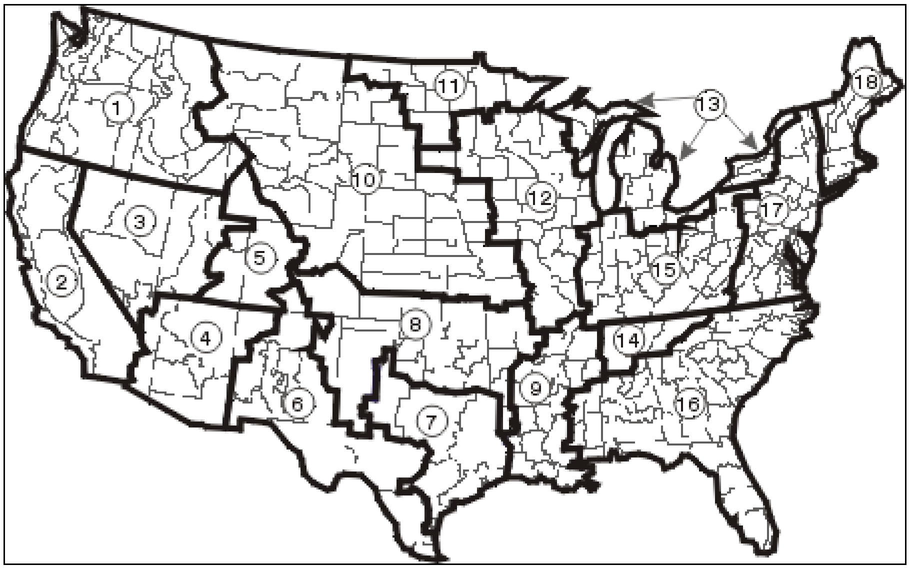
Figure 2.5: This map shows breaks the US down by climate region. The regions are color coded by the percent of time they have experienced drought events. The time scale for this map is 1895 to 1995. [3]

2.3 Drought in Texas

Agriculture has played a large role in Texas since its establishment as a state. Water scarcity and a water dependent economy have made Texas particularly vulnerable to drought. The most expensive weather disaster in the history of the United States is the drought of 1988. Damages from this event are estimated at $40 billion, predominately in the corn and soybean agricultural industry. The damages due to this event spread throughout several states in the mid-west and western United States. While drastic, this event is not isolated. [5] Less than a decade later in 1996 another drought hit the mid-west, causing nearly $5 billion of loss in Texas alone. [6] Two years later the drought, although brief, caused an additional $6 billion in total loss to the state of Texas. The following year action was taking, as House Bill 2660 was signed to legislation. House

Bill 2660 established minimum levels of water conservation in water conservation plans with in Texas. [10]

Drought events have occurred in Texas during every decade in this century. The map in Figure 2.6 shows the major climate regions of the United States according to the National Climate Data Center (NCDC). Region seven is the Texas Gulf Basin Region, this contains east Texas (it should also be noted that this region contains the Trinity River Basin). The graph below this map should the drought events of the past century. The height of the columns within the graph represent the percentage of region seven that were experiencing extreme drought at the time. [11]



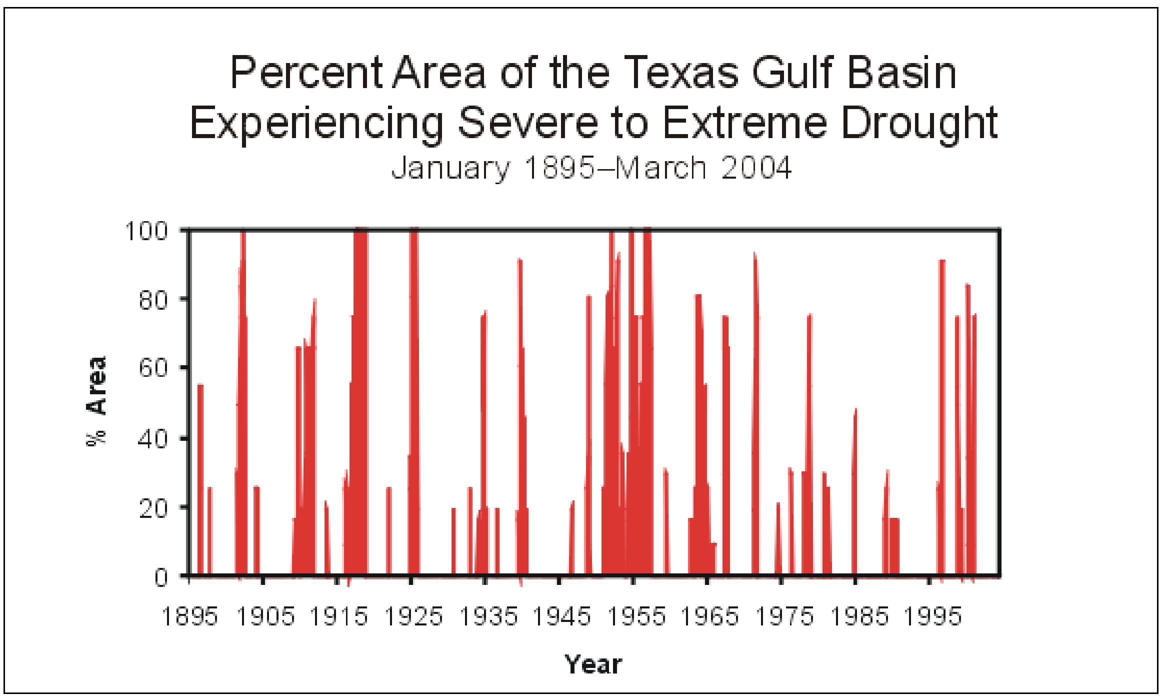


Figure 2.6: (Top) This map shows the NOAA climate regions of the US. Region 7 is the Texas Gulf Basin Region. (Bottom) The graph depicts the percent of the Texas Gulf Basin Region experiencing extreme drought conditions at a given time. [11]

Table 2.2 shows major recent droughts of Texas. Although not the most expensive, the largest Texas drought in recent history occurred in the middle of the twentieth century. The drought began in the 1947 and lasted a full decade until 1957. This drought had severe social and economic repercussions throughout the entire Great Plains, as it devastated the agricultural industry. Crop yields dropped as much as 50%. Meanwhile, ranchers suffered due to scorched grass and astronomical hay prices. By the time the drought subsided 244 of the 254 counties of Texas were declared to be in a state of federal drought disaster. [12]

Table 2.2: Major Recent Drought Events in Texas[13]

Major Recent Droughts of Texas
Time Period
1999-2000
1983-1984
1963-1964
1947-1957

2.4 Drought Mitigation and Planning

At this time, technology does not allow for the reliable prediction of drought events. However, monitoring drought helps to illustrate drought vulnerability and aid drought mitigation. By using drought-related information to aid decision makers, better plans and policies can be created to aid in the actions surrounding drought events. The most accepted tool in drought mitigation is drought preparedness planning. As outlined by Whilite and Svoboda, the three basic components of a drought plan are monitoring and early warning, risk assessment, and mitigation and response. [6]

During the past few decades the importance of drought preparedness planning has been realized by policy makers. In 1982, only three states of the United States had drought plans (Colorado, New York and South Dakota). However, today this trend has extended to most the states and to many countries around the world. [6] An outline for drought planning was developed in 1991 by Whilhite. This generic ten step process was developed and disseminated throughout the United States and internationally. Many regions have adopted this process in the creation of their drought preparedness plan, including Texas. The steps are as follows: [14]

1. Appoint a Drought Task Force
2. State the Purpose and Objectives of the Drought Plan
3. Seek Stakeholder Participation and Resolve Conflicts
4. Inventory Resources and Indentify Groups at Risk
5. Develop Organizational Structure and Prepare Drought Plan
6. Integrate Science and Policy, Close Institutional Gaps
7. Publicize the Proposed Plan, Solicit Reaction
8. Implement the Plan
9. Develop Education Programs
10. Post-Drought Evaluation

Although these ten steps may not seem that complicated, drought planning is a multifaceted task. Certain regions are more susceptible to drought impacts. Additionally, droughts propagate at different rates depending on the region. One way to address this problem is using an analytical tool such as a drought vulnerability tree diagram. Tree diagrams analyze drought vulnerability by significant drought impacts for a region. These show how susceptible a region is to specific drought risks. Two examples of a tree diagram are shown below. Figure 2.7 shows a tree diagram of agricultural impact analysis. Figure 2.8 is an example of tree diagram for urban drought impact analysis. The diagrams require many types of inputs due to the complex nature of drought analysis. [3]

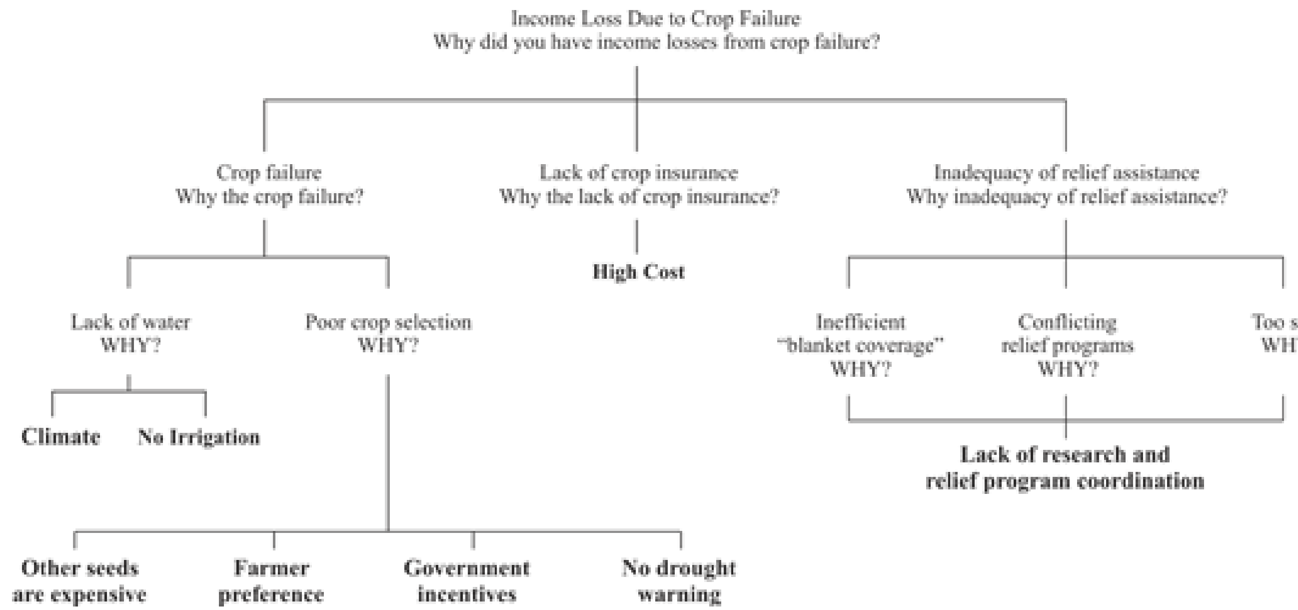


Figure 2.7: An example of a simplified agricultural impact tree diagram. (Notice the boldface represents the basal causes of the listed impact. Although these items may be broken down further, this example illustrates the vulnerability assessment process.) (From the National Drought Mitigation Center) [3]

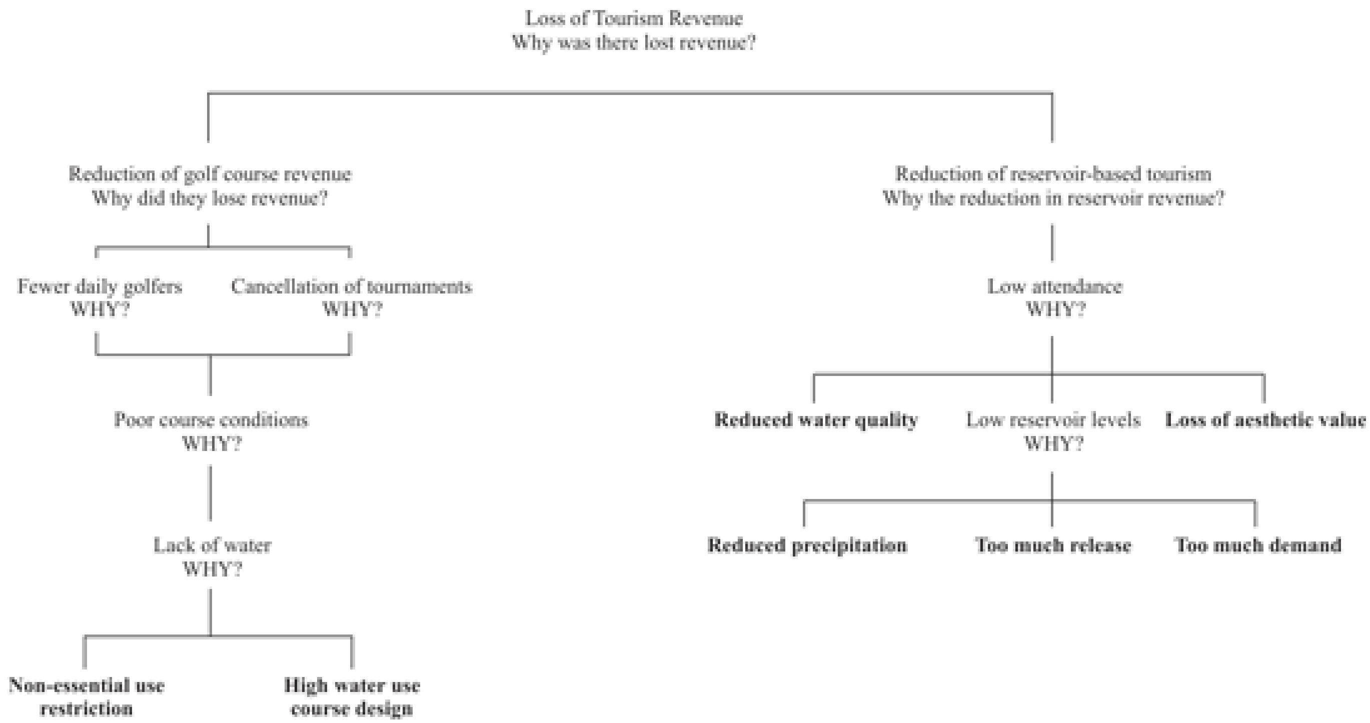


Figure 2.8: An example of a simplified urban impact tree diagram. (Notice the boldface represents the basal causes of the listed impact [in this case, the loss of tourism revenue]. Although these items may be broken down further, this example illustrates the vulnerability assessment process.) (From the National Drought Mitigation Center) [3]

In the United States, legislation to combat drought was introduced in the late nineteenth century. The settlement of the west had been hit hard by a drought that began in 1887 and ran into the 1890's. The legislation that followed focused predominantly on water management in the western United States. However, it wasn't until the late 1990s the United States began to address drought management as a nation. In 1998 the US Congress passed the National Drought Policy Act (Public Law 105-199). This Act created the base for establishing a national drought policy in order to improve drought preparedness and mitigation. Through this Act, the National Drought Policy Commission was created. [15]

In May of 2000, the US National Drought Policy Commission (NDPC) submitted a report to the Congress and the president concerning the state of drought preparedness in the US. The findings of this report showed that drought preparedness may have a strong impact on the reduction of social, economic and environmental impacts of drought. At the time of the report, 30 of the 50 US States had drought plans. However, much of the drought planning and federal funding for drought related projects that was in existence at the time was dispersed between various levels of groups. Through the 1990s the federal government funded 88 drought-related programs. Today all but five states have drought plans, as can been seen in Figure 2.9. After reviewing the state of drought programs the NDPC decided that to succeed in the development of national drought policy the guiding principles should be [6]:

1. Favor preparedness over insurance, insurance over relief and incentives over regulation.
2. Set research priorities based on the potential of the research results to reduce drought impacts.
3. Coordinate the delivery of federal services through collaboration with nonfederal entities.

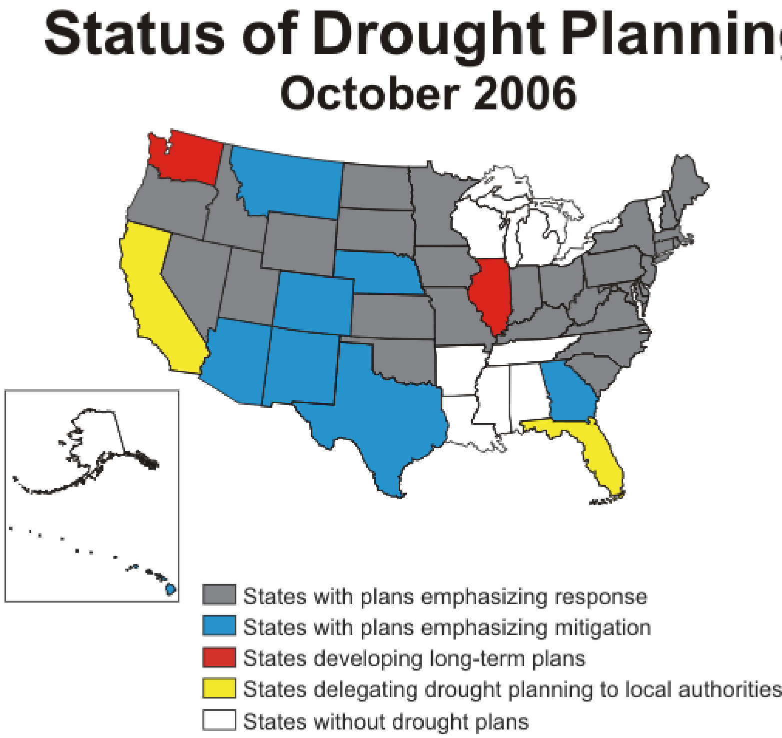


Figure 2.9: Drought plans in the United States. [3]

In meeting these goals the NDPC report stressed the importance of observation networks, monitoring, predication, information gateways and delivery, and research for effective drought preparedness. In relation to this, the NDPC found that federal monitoring programs joined with universities, private institutions and nonfederal entities provide the information required to form an effective drought preparedness and mitigation plan. To establish an effective drought mitigation system, a coordinated effort is needed to bring to information from different levels of the government and private sector. [15]

A current trend in developing drought mitigation schemes is to create an IDIS. IDIS compiles disparate data from multiple data systems and presents the data to be analyzed and used by decision makers. The systems aim to provide a tool that can help aid in the decision making process and serve as an early warning system. Currently, the creation of the NIDIS is underway under the direction of the NOAA and the NDMC. [6] If managed correctly, using reliable information an IDIS can be used as a drought early warning system for government agencies and the general public. Whilhite suggest that this can be obtained through pursuing the following objectives:

1. Adopt a viable definition of drought. By defining drought it will be possible to establish when a region is in or out of a drought phase. Often this is based on a climate variable index or a drought severity index.
2. Establish climatic regions for drought. Drought varies geographically. Therefore, areas of like geography should be managed in unison separate from other regions. For example, Texas has been divided into seven climate regions for managing drought. These regions were established by NOAA and adopted by NDMC and the state of Texas.
3. Developing key networks for monitoring drought. This should involved collecting data from climate monitoring systems and water supplies. In addition to monitoring climate parameters.
4. Establish the quality of the data and integrate the data.
5. Establish the needs of the stakeholders.
6. Develop a system to analyze drought information and disseminate to the necessary parties.

Possibly the most abstract of the IDIS project is the early warning system. [6]

2.5 Drought Mitigation and Planning in Texas

Following extensive and costly drought events in the mid-1990s the state of Texas began a movement towards drought preparedness. In 1998 action was taken, as House Bill 2660 was signed to legislation. This bill created the Drought Preparedness Council of Texas (DPC). As outlined by the bill, member agencies of the DPC are to support drought management and monitoring, assessment, preparedness, mitigation, and assistance efforts. The DPC was charged with the task of developing a comprehensive state-wide Drought Preparedness Plan. The bill outlines that the Plan should involve the following [10] :

1. Systematic data collection, analysis and dissemination of drought-related information;
2. An organizational structure that defines the duties and responsibilities and assures information flow among all levels of government;
3. An inventory of state and federal programs related to drought emergencies;
4. A mechanism to improve the timely and accurate assessment of drought impact;
5. Provision of accurate and timely information to the media.

To best manage this plan the state of Texas has been divided into seven climate regions (see Figure 2.10). Each region is issued a drought assessment level (1-advisory to 5-disaster). The assessment value is based on the climatological index, agriculture index and water availability index. A description of these indexes and their contributing data can be seen below. [10]

a. Climatological Assessment Index – Texas Water Development Board (TWDB)

(1) Standard Precipitation Index (SPI) – TWDB

(2) Keetch-Byram Drought Index (KBDI) – Texas Forestry Service (TFS)

(3) Vegetation and Temperature Condition index (VT) – TWDB

(4) Crop Moisture Index (CMI) – TWDB

(5) Palmer Drought Severity index (PDSI) – TWDB

b. Agriculture Assessment Index – Texas Agricultural Extension Service (TAEX)

(1) Soil Moisture Index – TAEX

(2) Crop Condition Index – TAEX

(3) Pasture and Range Condition Index – TAEX

(4) Livestock Sales Index – Texas Department of Agriculture (TDA)

(5) U.S. Department of Agriculture (USDA) Drought Declarations – TDA

c. Water Availability Assessment Index – TWDB

(1) Reservoir Levels – TWDB

(2) Stream flow Data – TWDB

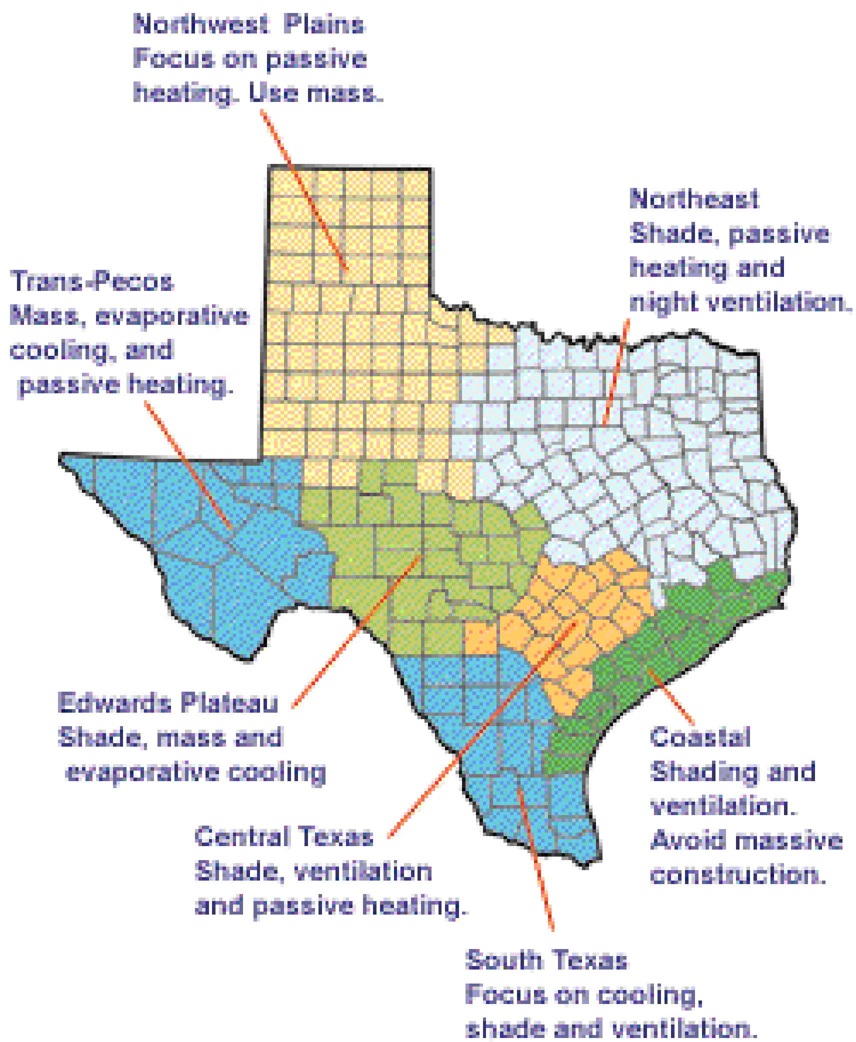


Figure 2.10: There are seven climate regions in Texas. The Trinity River Basin lies mainly in the Northeast Region. Its outlet is in the Coastal Region. [16]

One of Texas's involved agencies has been Texas Commission on Environmental Quality (TCEQ). In one of TCEQ's related documents, "A Drought Planning Guide for Public Water Systems in Texas" details that all water services must have a drought contingency plan. This plan lays out operations in case of extreme drought, periods of abnormally high water usage, supply contamination, or extended reduction in ability to supply water due to equipment failure. It is strongly suggested that the public be involved in the planning process. Typically water providers involve the public by forming citizen's advisory committees or task forces, holding public meetings, conducting surveys, seeking input directly from large-volume water customers (contractors, golf course operators, owners of car washes), or distributing a draft plan for public review and comment prior to adoption. Taking part in these events allows local residents (who will be affected by the drought contingency plan) an input to the plan and a familiarization with the plan. [17]

TCEQ's "A Drought Planning Guide for Public Water Systems in Texas" establishes five levels of drought, based on the "The Texas Drought Preparedness Plan", that can be seen below in Table 2.3. [10] Information about the counties impacted by a level of drought response can be found on the TCEQ website (http://www.tceq.state.tx.us/permitting/water_supply/pdw/trot/droughtw.html).

Table 2.3: The TCEQ's Drought Planning Guide for Public Water Systems in Texas Examples of Drought Response[18]

Level of Drought Response	**Type of Advisory**	**Typical Response to Advisory Level**
1	Advisory	Raise public awareness of the supply situation and request voluntary reductions in nonessential water use
2	Watch	Implement mandatory restrictions on certain non essential water uses
3	Severe conditions	Implement ban on certain non-essential water uses and water rate surcharge for excessive use
4	Critical conditions	Continue ban on nonessential water uses, increase water rate surcharge, activate backup wells
5	Emergency conditions	Initiate emergency response procedures

The IDIS website is one source of drought information. The idea of the IDIS for Texas is part of a greater drought information network called the NIDIS currently being developed by the NOAA. U.S. Public Law 109-430, the NIDIS Act of 2006, established the framework for this interagency approach to drought preparedness. The NIDIS Act aims to integrate data concerning physical/hydrological and socio-economic impacts. In order to better support decision making the NIDIS will provide a suite of tools for analyzing observational data. The NIDIS idea stemmed from the NDPC (2000). The ultimate goal of NIDIS is to mitigate the impacts of droughts. [19]

2.6 Integrated Information System Technology

There is currently little existing technology for integrated drought information systems. Developing these systems is a relatively new approach to mitigating drought. Because drought is an abstract and dynamic concept it is difficult to encapsulate it with policy or tools. To create a useful monitoring system, climate and hydrologic data must both be considered. Until recently, limitations in data management have limited drought monitoring. The World Meteorological Organization (WMO) reported a shift in drought mitigation in their 2006 publication, "Drought Monitoring and Early Warning: Concepts, Progress and Future Challenges." In this document, the WMO showed that several nations were attempting to develop drought monitoring systems to mitigate drought impact. Drought monitoring programs are being developed in China, the Great Horn of Africa, South Africa, Portugal, Australia, and North America (in particular the US). As monitoring, data management, data collection and the internet continue to develop, drought data integration services are becoming more apt to monitor and describe drought. [20]

The US began to develop an integrated drought information system in 1999. In 1999 NOAA, the USDA, and National Drought Mitigation Center formed an alliance to create the US Drought Monitor. The US Drought Monitor integrates information from climate indices to develop a unique drought index spatially for the entire US. This is discussed in further technical detail in section 3.4. Today, the US Drought Monitor has been expanded to include all of North America, the North American Drought Monitor

(NADM). However, the only data that the Drought Monitor provides is in the form of an index. [21]

The costly impacts of drought have forced states to make efforts towards drought mitigation. Every year the US battles drought. Texas has spent billions of dollars in drought recovery. The multi-dimensional nature of drought and its diverse impacts make it a difficult problem for planners and decision makers. IDIS incorporates the many facets of drought to present a more accurate picture of drought conditions and previous drought events. Through combining climate data, hydrologic data, and drought indices the IDIS offers a full scale image of how drought changes through time. This information will help decision makers, planners, researchers and the general public to better understand drought and aid in drought mitigation.

Chapter 3. Methodology

The Trinity River Basin represents a prototype for the Texas IDIS, as created for the Department of Texas Natural Resource Information Systems. The details of the prototype are discussed in chapter 4. This chapter presents over-arching ideas for creating an integrated information system for analyzing drought.

3.1 IDIS Preliminary Design

In its simplest form the IDIS has three components: a client, a web server and data servers. The client accesses the IDIS server as a website through the internet. The web server provides information automatically to the user, and also offers the user the option to retrieve data from additional data servers where data is stored. Upon receiving the data request from the client the IDIS is able to access data servers (such as NWIS) to retrieve the desired data. This is done through webservices. For certain types of data the IDIS automatically downloads databases and stores the data on the IDIS. This is done as a scheduled task in order to improve efficiency. These three components comprise the foundation of the IDIS. The basic idea of the structure is relatively simple. This allows the system to be more flexible. The structure of system dictates the types of data the system can support and the functions that the system can process. Figure 3.1 shows a schematic of the IDIS in relation to the client and data servers.

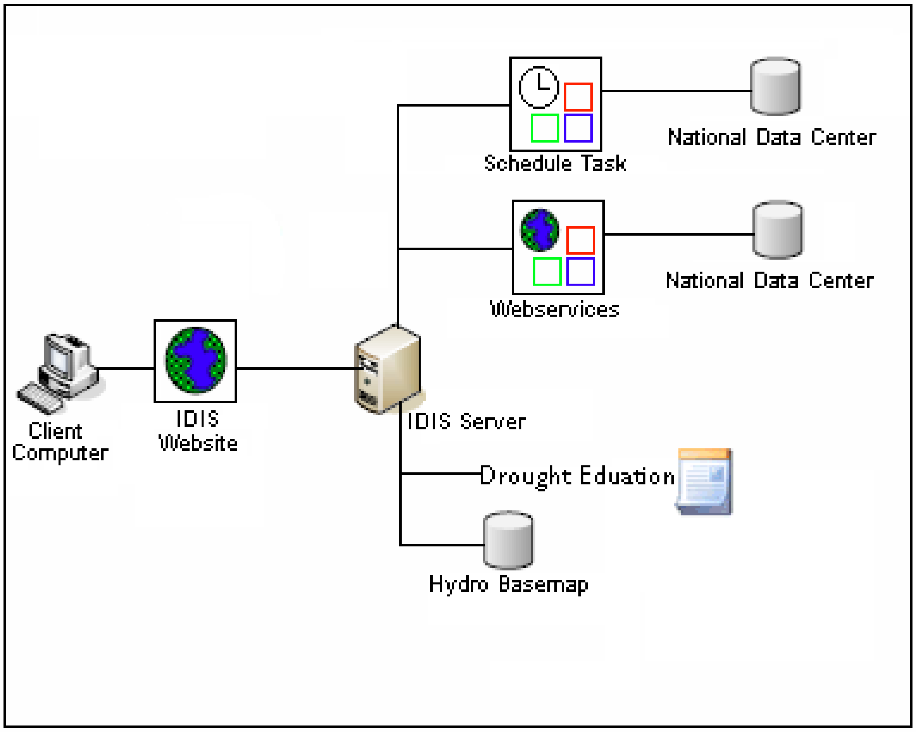


Figure 3.1: The IDIS links to the client and to national data centers.

The IDIS machine serves two types of data: static data and dynamic data. In Figure 3.2 the data below the server, labeled "A", or Hydro Basemap, is the static data. The Hydro Basemap is the static backdrop to the geographic information component of the IDIS. The features of the Hydro Basemap are contained within a geodatabase on the server, and work as a geographic reference for the dynamic IDIS data. The only data attached to the features are descriptors (ie, name or size). Although some of the features in the basemap may have aspects that change through time, they remain static for the hydro basemap and the IDIS. The features included in a hydro basemap are: flowlines, water bodies, roads, political boundaries, cities and towns, drainage basins and river basins. Also, located on the IDIS server is a document for drought education and internet links to websites that provide drought related information.

The data above the server is the dynamic data, labeled "B" in Figure 3.2. The data centers being accessed are national organization located in around the United States. The details of the data access processes and data centers are explained in greater detail in the following sections of this chapter. The dynamic data, also known as space-time data layers, are features, tables or rasters attached to data that change through time. These files are saved with another geodatabase, the Space_time geodatabase. Within this database are the features, rasters, raster catalog and tables. The raster catalog serves as an archive for raster images through time. The tables serve to format the feature classes and to link the individual features of a feature class to time series data.

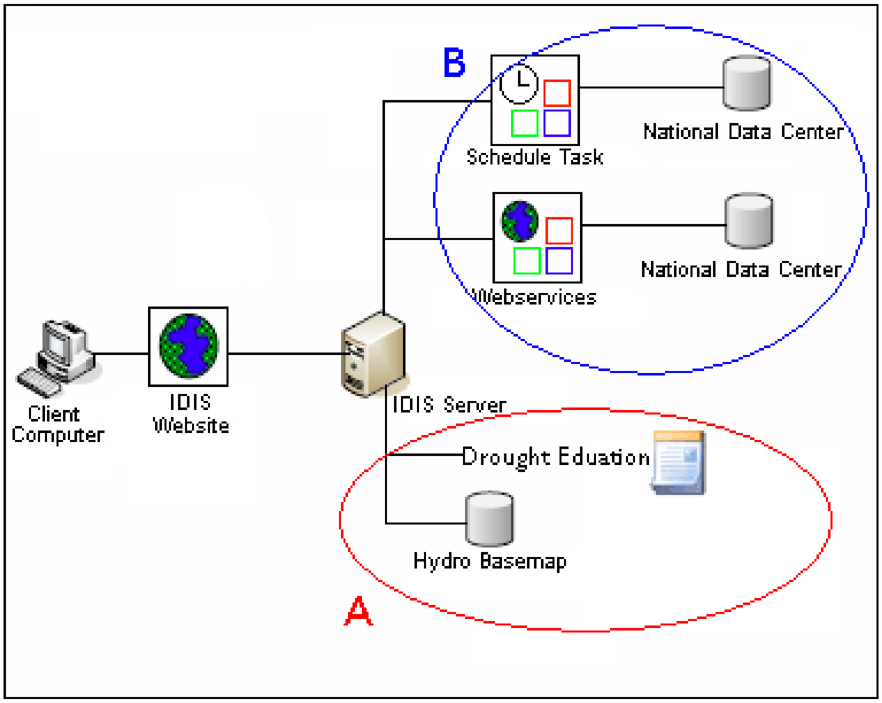


Figure 3.2: Circle A shows the static data and circle B shows the space-time data.

The items within the Space_time geodatabase share the fact that they are dynamic. However, they vary greatly in their nature. The first division within space-time data is how the data is stored. Some of the data is stored on the IDIS server and updated regularly downloads that are programmed scheduled tasks. Scheduled task use web services, but the user does not have input into this process. Other data is stored temporarily on the IDIS server and is retrieved only at the client's request, through web services. This explained in greater detail in sections 3.6 and 3.7.

Space-time data of the variables retrieved is attached to the dynamic features based on HydroIDs. Every feature in the Space_time geodatabase possesses a HydroID that allows it to be linked with the FeatureID of a piece of data. The data of the features and the variable data are managed in tables contained by the Space_time geodatabase. Table 3.1 shows a representation of the fields that are present in a Variable tables. This table serves as a catalog for all of the dynamic variables of the project. Table 3.2 shows a generic example of the fields in a time series table. The space-time data is formatted similarly to the Table 3.2. Table 3.1 provides details about the time series values (TSValues) given. More about this can be found in section 4.4.

Table 3.1: Variable Table Description

Field Name	**Field Description**
VariableID	Unique Numerical Identifier of the Variable
VarName	Variable Name
VarCode	Variable Code, Identifier for TStime Tables
VarUnits	Units of Measurement
VarDesc	Variable Description

Table 3.2: Time Series Data Description Table

Field Name	**Field Description**
FeatureID	Links to HydroID
TSTime	Date (Monthly Time Stamp)
VariableID	Variable TSValue

3.2 Hydro Basemap

The hydro basemap is the backdrop for the IDIS. The basemap serves as a reference for all of the features attached to data. The features of the basemap describe the geography of information system. For the purpose of the IDIS all of the features within the basemap are static. All of these features are stored as layers within a similar geodatabase. The data attached to features of the basemap is for the purpose of description. The features included within the basemap geodatabase are roads, towns, political boundaries, flowlines, water bodies, and drainage basins.

Political boundaries, roads, and town features- All of the non-hydrologic features of the IDIS are products of the TNRIS Strategic Mapping Program (StratMap). The StratMap is housed at TNRIS. It produces, maintains and enhances Texas digital geographic data themes. (TNRIS website) The StratMap is a comprehensive resource for geographic information for the state of Texas. The data in the StratMap is continuously refined and updated at TNRIS through partnerships with public and private organizations. Using this data for the Texas IDIS insures that the basemap data is of a statewide standard and of high quality. The political boundaries, roads and towns are important geographic references for the hydrologic features and drought data. This data is necessary to achieve the IDIS goals of public information and aiding decision makers.

Hydrologic features- Because drought is a function of the water cycle, the hydrologic features of the IDIS are imperative. Much of the data in the IDIS is linked to the hydrologic features (such as reservoirs and stream gauges). Even the hydrologic features that are static for the purpose of this project play important roles as references (such as the river basin boundary, flowlines and drainage basins). The hydrologic data features used for the IDIS come from the National Hydrography Dataset Plus (NHDPlus). NHDPlus is based on the National Hydrography Dataset (NHD). The NHD was developed by the USGS working with the Environmental Protection Agency (EPA). The USGS and EPA worked together using data from the National Elevation Dataset (NED) and the National Land Cover Dataset (NLCD) to produce a more exact hydrography for the nation. More information about this can be found at the Horizon Systems website: http://www.horizon-systems.com/nhdplus/. Figure 3.3 shows the NHDPlus features for the Trinity River Basin. [22]

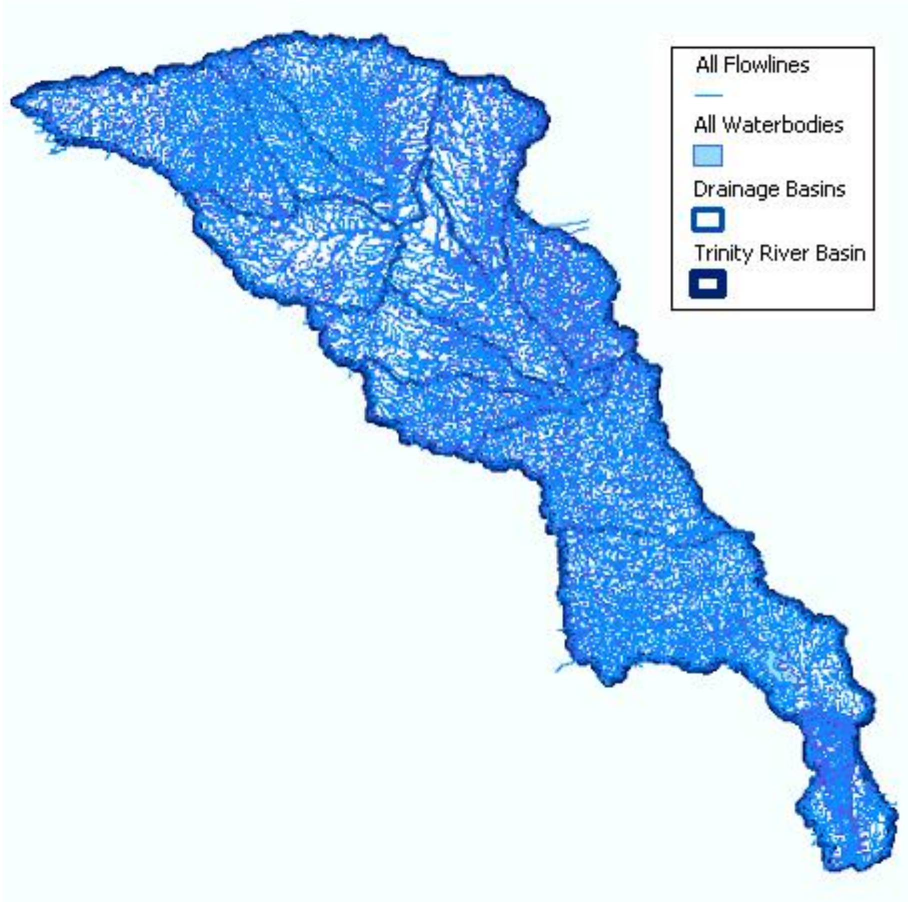


Figure 3.3: This figure shows the NHDPlus features for the Trinity River Basin. These features include flowlines, water bodies, drainage basins, and the river basin.

3.3 Space-Time Layers

The space-time layers of the IDIS are layers of features that are attached to data that is dynamic through space and time. These layers are critical to the IDIS project. They allow for depiction of the drought related variables through time. By analyzing these values the users are able to study drought better. Space-time layers offer a greater understanding to the relationship between meteorological, agricultural and hydrological droughts. Also, analyzing the time change functions of space-time values is enlightening towards comprehending the true state of drought that exists through time.

<u>Counties</u>- For the purpose of this project the entire NARR climate data has been linked with the counties layer (NARR data is described in section 3.4). This data entails model

data for many climate variables dating back to 1979. This project only uses a selection of these variables: soil moisture; subsurface runoff; non-infiltrating surface runoff; evaporation; potential evaporation; temperature; and precipitation. These variables were chosen because they describe the different stages of drought. The counties feature was used to support this data because counties are a relatively small area and they are a political boundary. Because counties represent smaller portions of the entire river basin they can be used to show climate variations within the river basin over time. Due to the size of the river basin, climate is able to vary within the basin. However, climate varies little within a county. Additionally, because a county is a political boundary this serves to help decision makers. Decisions typically based on political boundaries, not drainage basin boundaries. Other projects may put the counties layer in the basemap. However, for the objectives of the IDIS it is more useful to make counties a Space-time layer for climate data.

<u>Stream Gauges</u>- The stream gauge feature layer in the IDIS project is made of USGS gauges. These gauges represent the stream gauge network attached to the USGS NWIS data server. The NWIS data server contains real time stream flow data for all of the gauge features within the feature layer. The gauges can be linked to their data on the NWIS website through their HydroID. The HydroID of each gauge feature matches the USGS gauge number identifier. To obtain the data, the IDIS client selects a gauge and input a specific date. IDIS inputs this information into a web service, which then extracts this data for NWIS. This process is described in greater detail in section 3.6.

<u>Reservoirs</u>- The IDIS links reservoirs with data from the USGS NWIS website also. The NWIS website offers daily values for reservoirs across the US. More about the reservoir data provided by NWIS can be found in section 3.4. However, it is important to address the difference between the water bodies feature layer and the gauged reservoirs feature layer. The water bodies layer is created from the NHDPlus, whereas the gauged reservoirs feature layer comprises only reservoirs that are monitored by the USGS. The features of the gauged reservoir layer are all identified with HydroCodes that match the USGS numerical identifiers for the reservoirs. IDIS clients select a reservoir and input a

date range. This information is input to a web service (similar to that of the stream gauges) and returns the requested data. More about this process can be found in section 3.6.

Reservoir Depth- In 1991 the Texas Legislature authorized the TWDB to begin doing volumetric surveys of the state's reservoirs. Since 1993 the Surface Water Section of the TWDB has done surveys on 52 of the 77 major reservoirs of Texas. Additionally, surveys have been on many of the smaller reservoirs of Texas. For many of the reservoir of Texas storage volumes were calculated using topographic maps upon their creation. However, due to constant sediment deposition over time these volumes have changed. New bathymetric surveys provide a better analysis of the water volume available in a reservoir. [23]

Bathymetric surveys are created using satellite technology from Global Positioning Systems (GPS), Differential Global Positioning System (DGPS), acoustic depth sounder for data-collection, and GIS software. Reservoirs are surveyed by boat. The boat is equipped with the sounding devise and positioning systems. By transecting the reservoir (in 500ft intervals) an estimate of lake bathymetry is collected. This data is then processed using GIS to create an estimated surface of the lake floor. GIS uses Delaunay Triangulation to create this lake floor surface, called a TIN (Triangulated Irregular Network). Ongoing studies show that error generated by using Delaunay Triangulation can be minimized by interpolating between the sounding points.[23] Figure 3.4 shows an example of the a TIN for Lake Grapevine, in the Trinity River Basin. Figure 3.5 shows an image of a depth raster of the Lake Grapevine. This image was created by using raster math to subtract a given reservoir elevation from a rasterized version of the TIN. More about this process can be found in section 3.4.

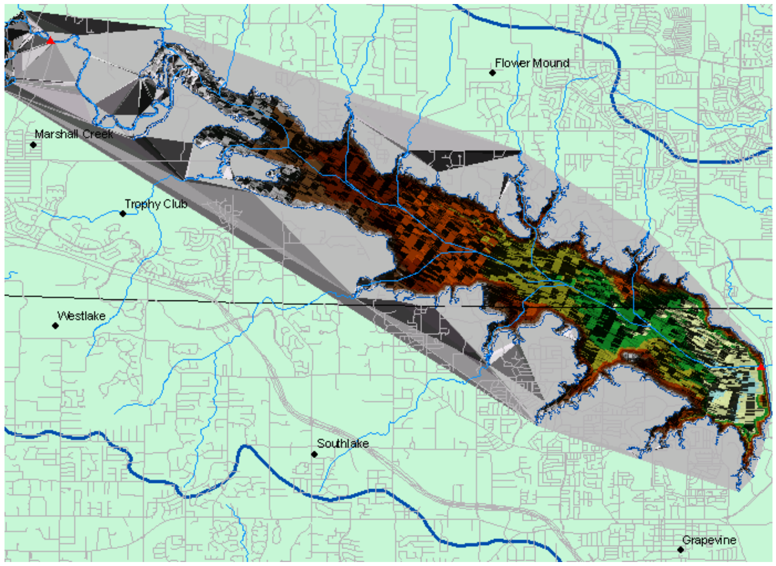


Figure 3.4: This image shows a TIN of Lake Grapevine, in the Trinity River Basin.

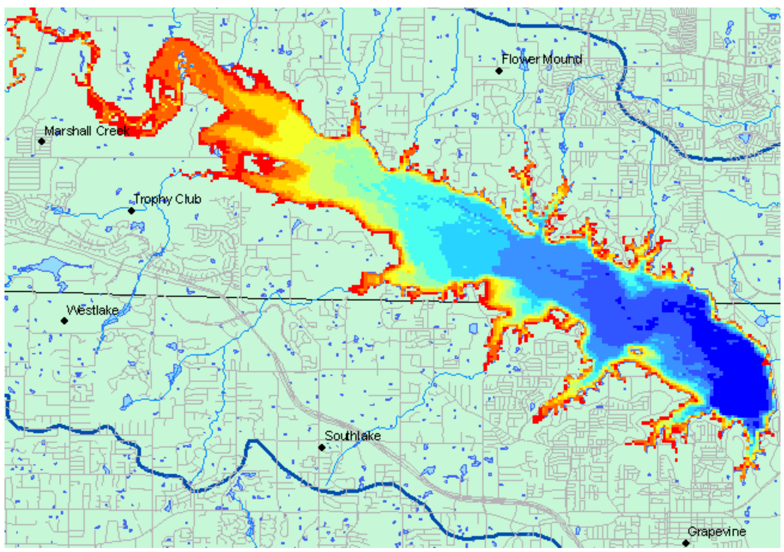


Figure 3.5: This image shows a raster of the depth of Lake Grapevine, based on lake elevation and the lake TIN.

In the IDIS project depth rasters are created each day based on the previous day's reservoir elevation. This is accomplished using a programmed scheduled task coupled with web services. More about this process can be found in section 4.5. These rasters are stored and archived in a raster catalog.

Drought Indices- The drought indices differ from the other space-time layers because they are geographically dynamic feature layers. Thus far, all of the space-time layers described have been static features attached to dynamic time series data. The drought indices are raster images that change on a regular basis (for the drought indices used in the project the change in monthly). The drought indices used in this project are all obtained using weekly scheduled tasks. The images themselves may change from week to week, but they do not possess any data that describes their action through time. The indices featured in this project are the US Drought Monitor, the Drought Impact Reporter and the Corp Moisture Index. More about these indices can be found in the next section.

3.4 Sources of Drought Information

To get a full understanding of drought at all of its stages through the varying climatic regions of Texas a spectrum of information is needed. Different sources of information are described below:

<u>North American Regional Reanalysis (NARR) Data</u>- The NCEP completed the NARR project in 2004. The NARR defined as a “long-term, dynamically consistent, high-resolution, high-frequency, atmospheric and land surface hydrology dataset for the North American domain.” The NARR represents a period from 1979 to the present. The components used to create the NARR are the NCEP Eta Model and its Data Assimilation System, a version of the NOAA land surface model and many additional data sets. The additional data sets are used as input values to the Eta Model and NOAA land surface model. Due to the assimilation of information used to create the NARR, a better representation of land-atmosphere interaction has been created. Some of the produced variables (such as precipitation and evaporation) have been improved by the Regional Assimilation System (RDAS). The models are run on a three hour integration analysis. The results are available on a 32 km grid resolution, similar to the Eta model before 2000. The area covered by NARR can be seen in Figure 3.6. [24]

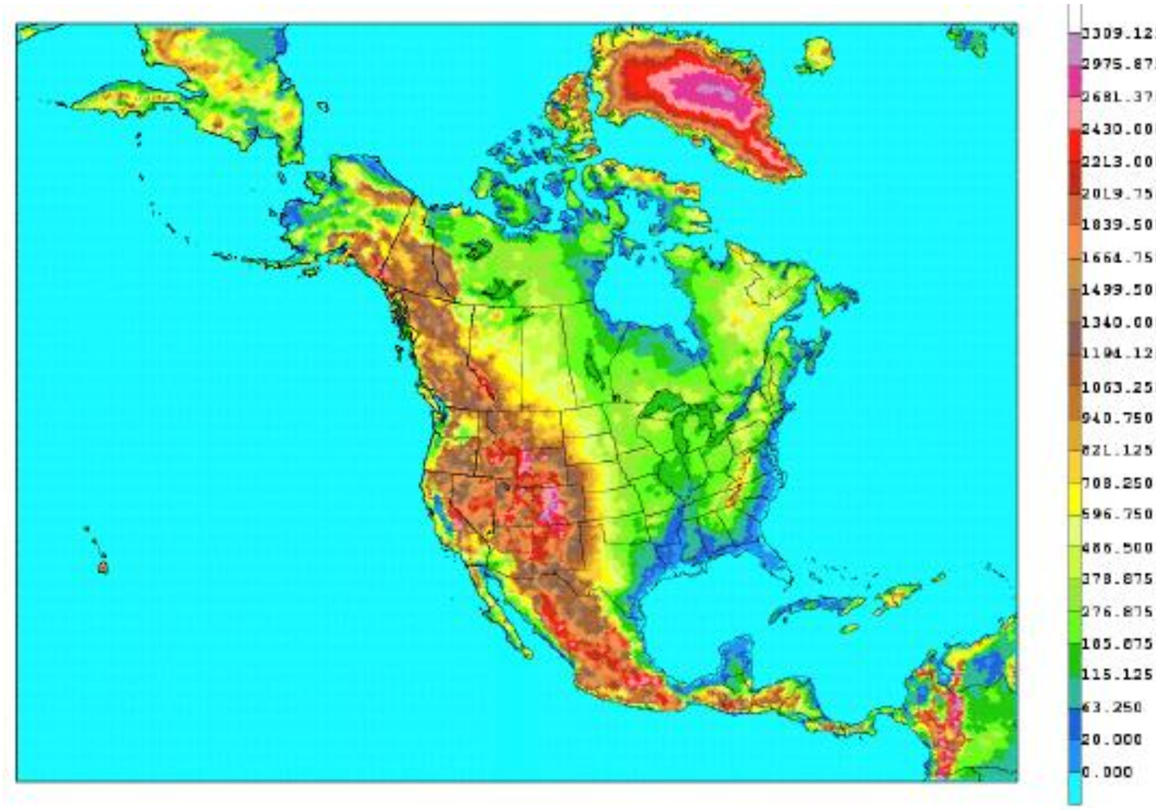


Figure 3.6: the NCEP regional Reanalysis domain and its 32 km topography. Terrain elevation (m) is indicated by the color scale at the right. [24]

The NARR data is available for download online at the NOAA National Operational Model Archive and Distribution System (NOMADS) from the Thematic Real-time Environmental Distribution Data Service (THREDDS) Data Server (TDS). The data is available as NetCDF files. The catalog of NARR data exists in two timestep formats: three hour intervals and monthly averages of the three hour time steps. The three hour time steps are based on Coordinated Universal Time(UTC), starting at 0-3 hours and going until 21 to 24 hours. The NARR values are cumulative for each timestep. This project uses the monthly average timestep data. IDIS obtains NARR data through scheduled task downloads using web services. [24] The IDIS project uses seven variables from NARR: temperature, potential evaporation, evaporation, soil moisture, subsurface runoff, non-infiltrating surface runoff and precipitation. Appendix B shows tables and graphs detailing the data.

Temperature- The temperature is given in degrees Kelvin. The time step value is the average for the 3 hour period. The monthly mean value is the average of all of the 3 hour time steps in the month.

Potential Evaporation- The potential evaporation represents the potential water vapor capacity of the air. The values are given in mm or kg/sq meter over 3 hours (cumulative for the 3 hour period). The monthly average is the average of the 3 hour time steps over all days of that month. To find the total potential evaporation or evaporation for a given month the NARR value would need to be multiplied by the total number of 3 hour timesteps that occurred during that month (eight periods a day for 28 to 31 days).

Evaporation- The evaporation variable is a measurement of the actual evaporation that occurs. Evaporation is limited by the amount of water in the soil available to be evaporated. The evaporation demand of the air (potential evaporation) is typically less than the actual evaporation. The difference between potential evaporation and evaporation is greater in more arid areas or drier times of the year. The values are given in mm or kg/sq meter over 3 hours (cumulative for the 3 hour period). The monthly average is the average of all the 3 hour time steps for that month. To find the total potential evaporation for a given month the NARR value would need to be multiplied by the total number of 3 hour timesteps that occurred during that month.

Precipitation- The precipitation represents the potential water vapor capacity of the air. The values are given in mm or kg/sq meter over 3 hours (cumulative for the 3 hour period). The monthly average is the average of all the 3 hour time steps for that month. To find the total precipitation for a given month the NARR value would need to be multiplied by the total number of 3 hour timesteps that occurred during that month.

Soil Moisture- The soil moisture is a measure of the volume present in the top 100 cm of the soil. The values are given in mm or kg/sq meters present on average over a 3 hour period. The monthly average is the average of all the 3 hour time steps for that month.

Subsurface Runoff Baseflow- The subsurface runoff baseflow is the precipitation runoff that infiltrates the surface. The values are given in mm or kg/sq meter over 3 hours (cumulative for the 3 hour period). The monthly average is the average of all the 3 hour time steps for that month. To find the total precipitation for a given month the NARR value would need to be multiplied by the total number of 3 hour timesteps that occurred during that month.

Surface Runoff Non-infiltrating- The surface runoff non-infiltrating is the precipitation runoff that does not infiltrate the surface. The values are given in mm or kg/sq meter over 3 hours (cumulative for the 3 hour period). The monthly average is the average of all the 3 hour time steps for that month. To find the total precipitation for a given month the NARR value would need to be multiplied by the total number of 3 hour timesteps that occurred during that month.

Stream gauge data- USGS monitors data from approximately 1.5 million sites across the U.S. All of the USGS data, from 1857 when monitoring began to the present, is stored on National Water Information System Web Site (NWISWeb). The streamflow network was established to meet various needs for streamflow information. The information is used to for water supply management, flood monitoring and environmental observation. The objective of each gauge station is to produce a continuous record of stage and discharge at that specific location. Streamflow is measured instantaneously and averaged over time. The stream data that is collected by the gauges is recorded at fifteen to sixty minute intervals onsite, and then transmitted to a USGS office every one to four hours. Each site is selected based on the needs of water management or by the requirements of the hydrologic network. Due to the restrictions on gauge locations, sometimes artificial control structures (such as low dams, broad-crested weirs or flumes) must be built in a stream channel to stabilize the stage and discharge data. [25]

USGS presents the national streamflow network data in time series available on the NWISWeb. Data is typically recorded as gauge height (in feet) and discharge (in cubic feet per second). Figure 3.7 shows USGS stream gauges for the state of Texas. In addition to stage and streamflow information, the NWISWeb also offers information about water quality and well level. The NWISWeb organizes the data on the website through watershed address. This data can then be access by users through web services. [25]

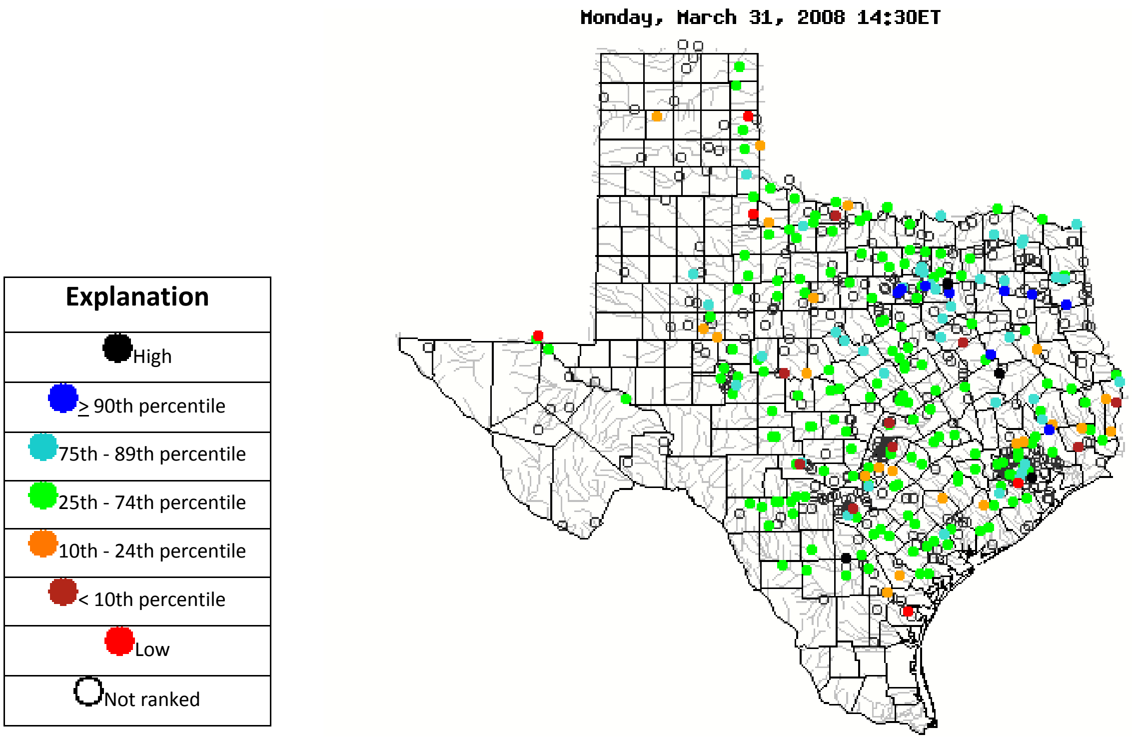


Figure 3.7: This map shows the stream gauges in Texas. The map depicts the stage of flow in the streams being measured on March 31, 2008. [26]

<u>Reservoir Gauge Data</u>- In addition to stream gauges the NWIS system also supports data on reservoirs. Unlike streamflow data this data is collected daily. Because reservoir elevation does not change as frequently as stream gauge data it is not necessary to represent data instantaneously. Stream gauges obtain water surface height (in feet). This is accomplished through a variety of methods. For example, Figure 3.8 shows a schematic of a stilling well and shelter gauge station. (http://nationalatlas.gov/articles/water/a_streamflow.html) Elevation may also be sensed using bubble gauge which uses a gas-purge system. [25]

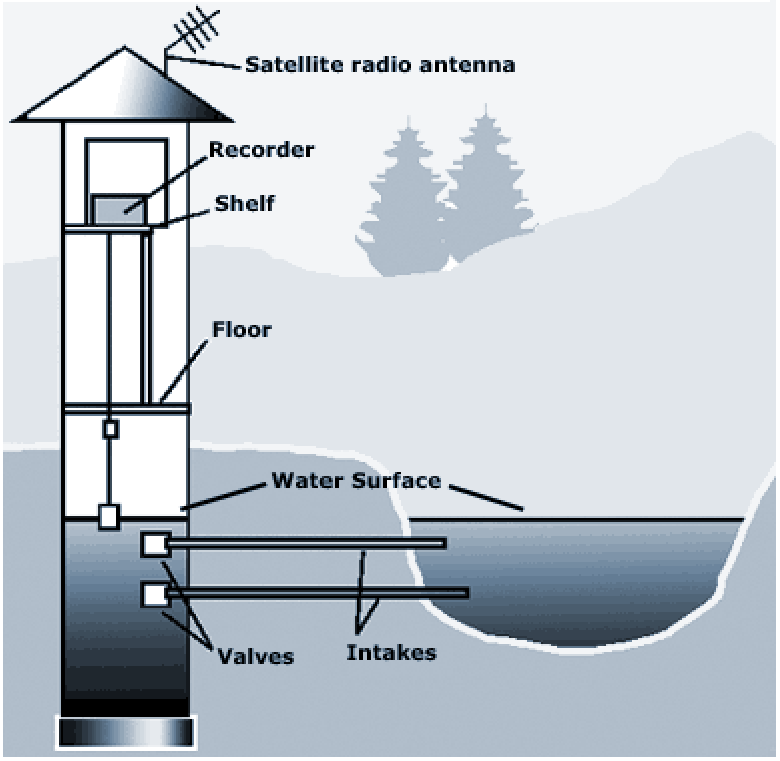


Figure 3.8: A schematic of a stilling well and shelter gauge station for measuring water surface elevation. [25]

Not all of the reservoirs within the Trinity River basin are monitored by NWIS. Table 3.3 shows a list of the reservoirs that are monitored by NWIS in the Trinity River Basin.

Table 3.3: This table is a list of the reservoirs in the Trinity River Basin that are monitored by the USGS. [27]

USGS Reservoirs of the Trinity River Basin	
Gauge Number	Reservoir name
8042820	Lost Ck Res nr Jacksboro, TX
8043000	Bridgeport Res abv Bridgeport, TX
8043700	Lk Amon G Carter nr Bowie, TX
8045000	Eagle Mtn Res abv Ft Worth, TX
8045400	Lk Worth abv Ft Worth, TX
8045800	Lk Weatherford nr Weatherford, TX
8046500	Benbrook Lk nr Benbrook, TX
8049200	Lk Arlington at Arlington, TX
8049800	Joe Pool Lk nr Duncanville, TX
8050050	Mountain Ck Lk nr Grand Prairie, TX
8051100	Ray Roberts Lk nr Pilot Point, TX
8052800	Lewisville Lk nr Lewisville, TX
8054500	Grapevine Lk nr Grapevine, TX
8060500	Lavon Lk nr Lavon, TX
8061550	Lk Ray Hubbard nr Forney, TX
8062730	New Terrell City Lk nr Terrell, TX
8063010	Cedar Ck Res nr Trinidad, TX
8063050	Navarro Mills Lk nr Dawson, TX
8063600	Lk Waxahachie nr Waxahachie, TX
8063700	Bardwell Lk nr Ennis, TX
8064510	Halbert Lk nr Corsicana, TX
8064550	Richland-Chambers Res nr Kerens, TX
8065330	Houston County Lk nr Crockett, TX
8066190	Livingston Res nr Goodrich, TX

US. Drought Monitor- The US Drought Monitor produces weekly images of drought severity for the United States, as can be seen in Figure 3.9. The US Drought Monitor bases its drought severity on a blend of indices, including the PDSI, the CPC Soil Moisture Model, Standardized Precipitation Index (SPI), USGS weekly streamflow percentiles, and objective short and long-term drought indicators. The maps are produced by the NDMC and the University of Nebraska-Lincoln in collaboration with several federal, state, academic and independent organizations. Links to this data are provided on the US Drought Monitor website, as well as, archived data. [3]

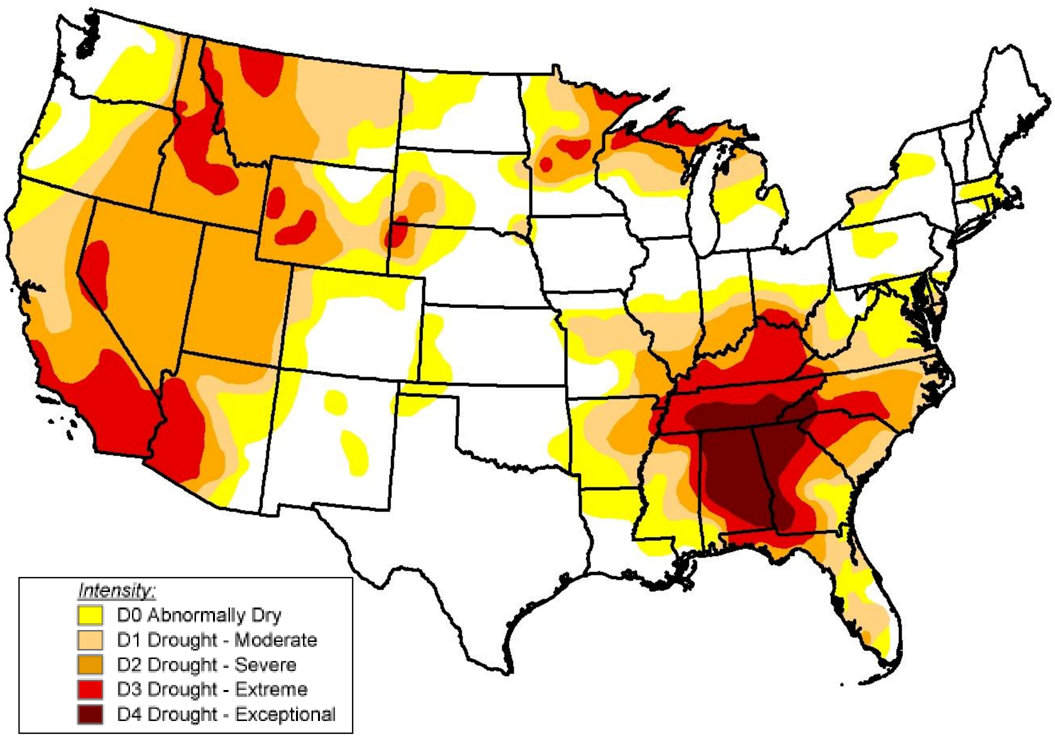


Figure 3.9: The US Drought Monitor for the week of August 28th, 2007. [3]

The US Drought Monitor is largely based on the PDSI, which is the most commonly used index for assess drought. The PDSI calculation was created in 1965 by W.C. Palmer as a means for evaluating soil moisture. However, the method he developed has been used widely to establish drought severity. Palmer defined drought as "an interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply."[18] The PDSI is calculated using monthly values for precipitation, potential evapotranspiration, and available moisture stored in both the surface and underlying soil layer. Although the PDSI is the most widely accepted method for defining drought severity, it is an imperfect method. The PDSI is lacking in three major issues. First, the PDSI fails to take into account agricultural irrigation. Second, it does not take into account for water stored in snow or in man-made reservoirs. And third, it cannot take into account water conservation measures. Table 3.4 shows the classification system that the NDMC uses to establish drought level. [28]

Table 3.4: This table shows drought classification for the US Drought Monitor. [3]

Drought Severity Classification							
		RANGES					
Category	**Description**	**Possible Impacts**	**Palmer Drought Index**	**CPC Soil Moisture Model (Percentiles)**	**USGS Weekly Streamflow (Percentiles)**	**Standardized Precipitation Index (SPI)**	**Objective Short and Long-term Drought Indicator Blends (Percentiles)**
D0	Abnormally Dry	Going into drought: short-term dryness slowing planting, growth of crops or pastures. Coming out of drought: some lingering water deficits; pastures or crops not fully recovered	-1.0 to -1.9	21-30	21-30	-0.5 to -0.7	21-30
D1	Moderate Drought	Some damage to crops, pastures; streams, reservoirs, or wells low, some water shortages developing or imminent; voluntary water-use restrictions requested	-2.0 to -2.9	11-20	11-20	-0.8 to -1.2	11-20
D2	Severe Drought	Crop or pasture losses likely; water shortages common; water restrictions imposed	-3.0 to -3.9	6-10	6-10	-1.3 to -1.5	6-10
D3	Extreme Drought	Major crop/pasture losses; widespread water shortages or restrictions	-4.0 to -4.9	3-5	3-5	-1.6 to -1.9	3-5
D4	Exceptional Drought	Exceptional and widespread crop/pasture losses; shortages of water in reservoirs, streams, and wells creating water emergencies	-5.0 or less	0-2	0-2	-2.0 or less	0-2

Drought Impact Reporter-The NDMC created the Drought Impact Reporter to catalog drought impacts through the United States. Because drought is difficult to quantify, the Drought Impact Reporter was established to help measure the effects of drought through time. Understanding impacts helps to establish the risks associated with drought. The impacts are linked spatially by county. On the Drought Impact Reporter map states and counties are color-coded to represent the number of drought-related events have occurred. Maps can be created by time period of events ranging from the past week to the past year. The impacts are recorded from over 5,000 online news sources and reports submitted by individuals (private citizens and government officials) online. Additionally, the impacts are divided into six types of drought related events: agriculture, water/energy, environment, fire, social and other. Figure 3.10 shows the Drought Impact Report for Texas March 31st, 2008. [29]

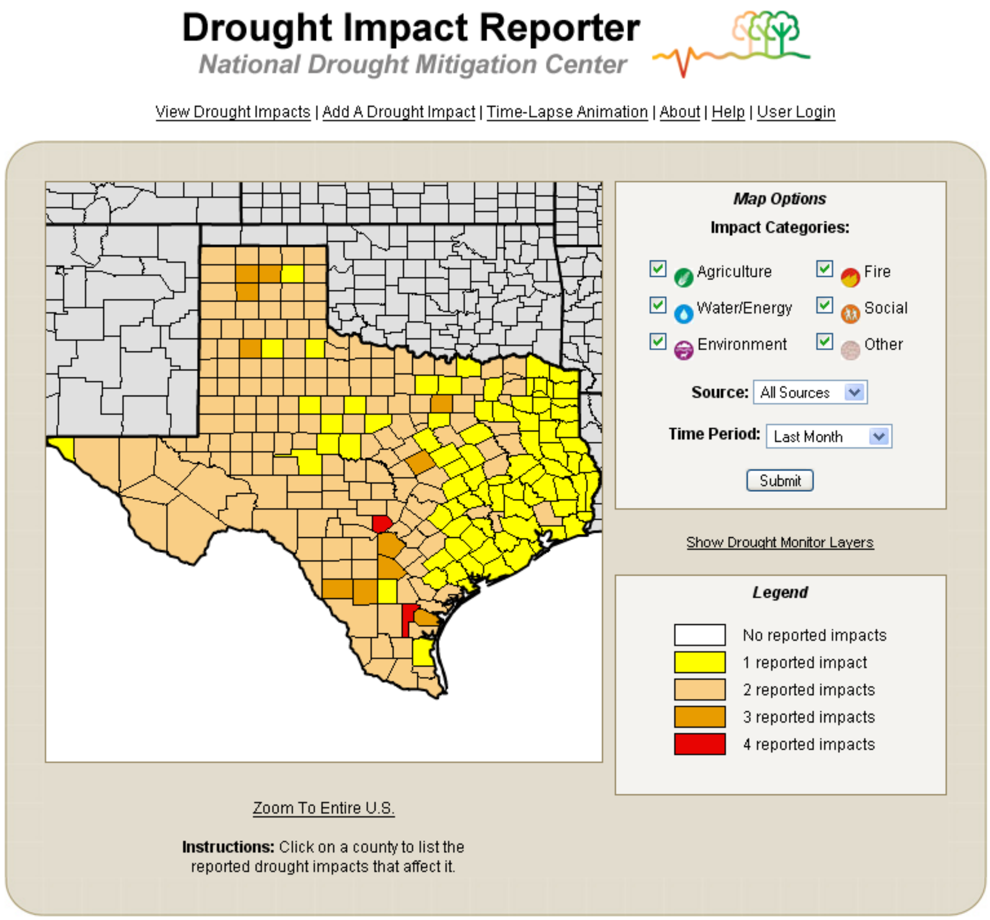


Figure 3.10: This shows the drought impacts reported in Texas the week of March 31st, 2008. [29]

Crop Moisture Index- The Crop Moisture Index (CMI) is produced by NOAA's Climate Prediction Center (CPC). The CMI uses meteorological data to monitor crop conditions. The index is produced weekly for the each of the NOAA climate regions. Figure 3.11 shows the CMI for the week of April 1st, 2008. The climate regions used in this project are 113, 114, 116, and 118. The CMI was developed by Palmer in 1968 as part of the PDSI. The scale is based on the mean temperature and precipitation from the past week. A negative three indicates the driest conditions possible, a positive three indicates the wettest conditions possible, and a zero indicates that the precipitation and temperature have been average for the region for that time of the year. [28]

The CMI is an excellent measure of short term drought conditions. This was developed as a tool for the agriculture industry in planning for crop planting. However, the results of the CMI may be misleading concerning the long term outlook for climate conditions. If a weather event lasts longer than a year, it begins to affect the mean annual temperature and mean annual precipitation. Therefore, if a drought lasts for several years, the CMI becomes less useful. [30]

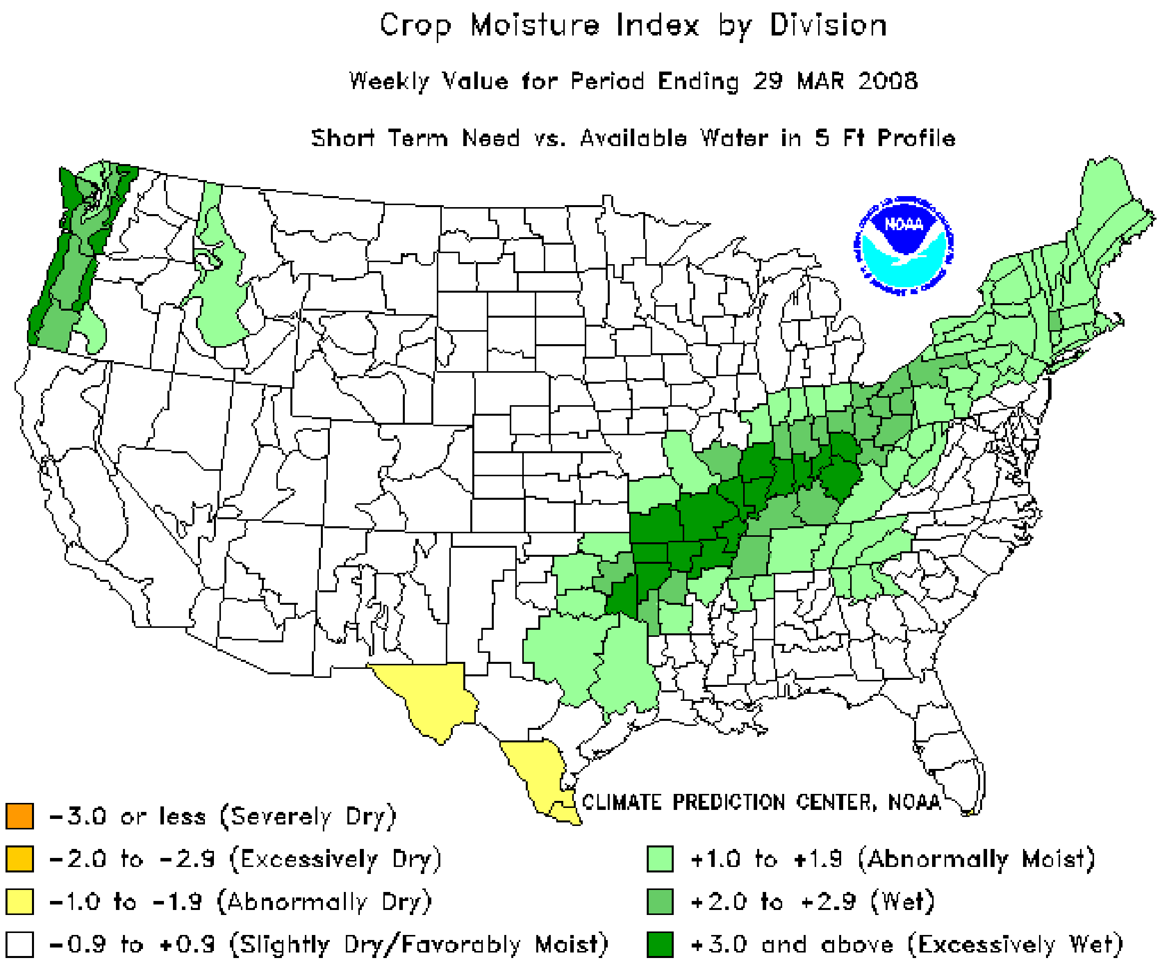


Figure 3.11: This image shows the CMI for the United States March 29th, 2008. The image was created the following week. [30]

3.5 Integrating Information

As mentioned in section 3.3, the data used in IDIS comes in several different formats. GIS is a sophisticated tool, which allows for the incorporation of several types of data. However, for every type of data that is input into the IDIS, a system must be developed integrate this data. Often, the GIS software provided tools to enable a simple integration. However, sometimes the integration programs had to be written. The most of the codes where developed using Python script.

Network Common Data Form (NetCDF) File- NetCDF files are in a binary data format. They are a standard form exchanging scientific information. NetCDF was developed by University Corporation for Atmospheric Research (UCAR). [31] They're commonly used for remote sensing data products such as NEXRAD, and in the case of this project, NARR. ArcGIS tools have been developed for converting this format into GIS friendly forms. The tools developed can be found in the Multidimensional toolbox of Arc 9.2. The toolbox is shown in Figure 3.12. These tools were used to integrate the NetCDF files into the IDIS project, in conjunction with several other ArcGIS tools. The tools were strung together using Model Builder to process the NetCDF files into a form usable for the IDIS system.

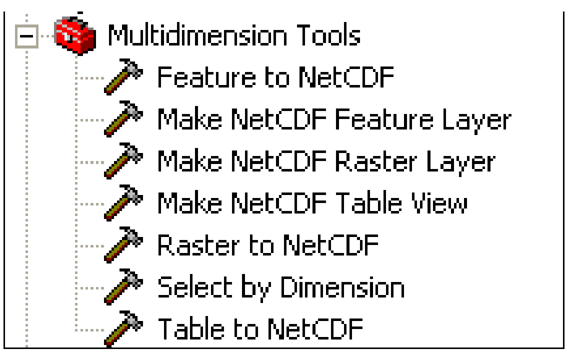


Figure 3.12: This is the ArcGIS Multidimension toolbox. Its tools are useful for working with NetCDF files in GIS.

There are several steps and tools needed to integrate the NetCDF files. NARR provides NetCDF files for every month. As mentioned in previous sections the NARR data contains monthly averages of climate data for North America. The NARR climate variables used in this IDIS project are precipitation, temperature, potential evaporation, evaporation, subsurface runoff, non-infiltrating surface runoff and soil moisture. These variables were chosen because of their pertinence to drought conditions. A catalog of NetCDF files for these variables from 1979 to the previous month has been stored on the IDIS server. Every month this catalog is updated with the previous month's data. This is done using schedule tasks described in the next section.

To convert the NetCDF files, the ArcGIS model created was exported into python code, and incorporated into a code that was made into an additional scheduled task to take place every month after the new data has been loaded to the server. Figure 3.13 shows an image of the ArcGIS model used for this task in model builder. The model created in model builder converts the NetCDF file into a feature layer. The feature layer created is a grid of points. The model then saves the feature as an actual layer so that it can be used in the next step, the spatial join. The grid points of the NARR data are then joined to the counties layer using a spatial join. In this step in the process it is important to select the one-to-many option. This aggregates values for grid points contained within the same county. At this point a county file containing climate data has been created for every date. The next step of the model merges all of these county layer files. Finally, the attribute table of the final merged file is cleaned up. All of the unnecessary fields in the table are deleted, and necessary fields are renamed to fit within the naming convention specific to the IDIS. More about the python code for this integration task can be found in Appendix C.

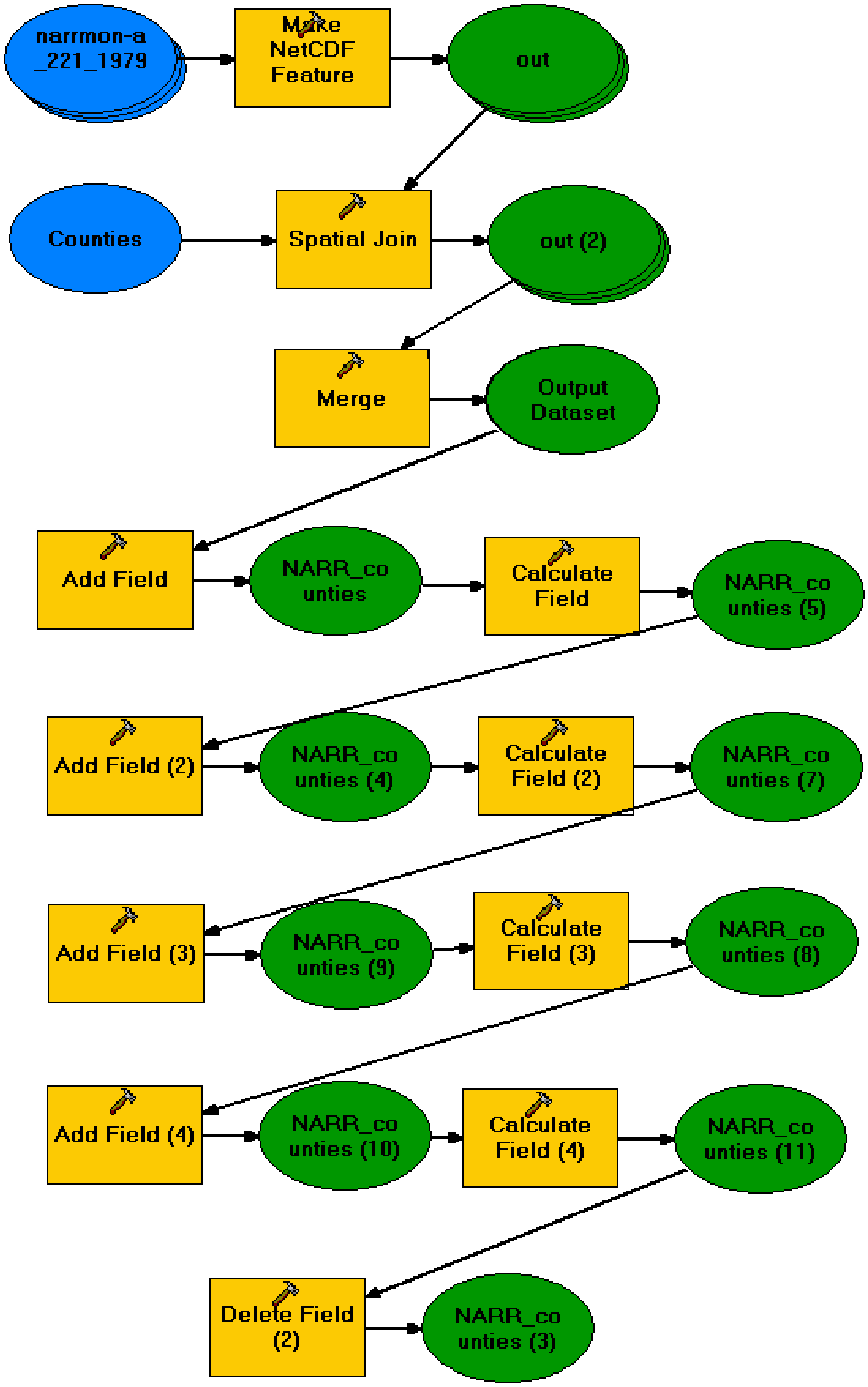


Figure 3.13: This tool was created using ArcGIS to integrate NetCDF files from NARR.

Comma-Separated Values (CSV) table with feature- This process for the IDIS is still being developed. However, the idea of linking CSV files with features is described here. Data downloaded from USGS NWIS is returned in a CSV table. This data is obtained using web services and must be integrated quickly (on-the-fly). Web services are described in more detail in the next section. This table is relatively simple to process, and easily links to GIS features. In the case IDIS, NWIS data is used to obtain information about reservoirs and stream gauges. Data from NWIS is linked to hydrologic features of reservoirs and stream gauges through a join of unique identifiers. NWIS has assigned each reservoir and stream gauge a unique identifier from USGS. IDIS has assigned all features to be attached to data with a unique identifier, called a HydroID. In the case of the reservoirs and stream gauges, the HydroIDs match the NWIS identifiers. There for the CSV data table can be quickly linked to the hydrologic features as the data is obtained from web services.

Comma-Separated Values (CSV) table with raster- IDIS uses a schedule task to download reservoir elevation daily from the USGS NWIS website. More can be learned about this process in the next chapter. This data is retrieved in a CSV table format. After retrieving this data daily it must be integrating into the IDIS system so that it is obtainable to users. One of the methods for data display is to use the reservoir elevation level information to create showing reservoir depth based on the current reservoir elevation. Like the data retrieved, this is accomplished through a scheduled task. Similar to the NetCDF integration described above, this process was developed using ArcGIS Model Builder and python code.

First a model was created in ArcGIS Model Builder. Then the model was exported to python code. The code was then developed further to incorporate the data from the CSV file. The model used can be seen in Figure 3.14. The input to the model is the elevation data from the CSV file and rasters of the lake bathymetry. The rasters have been pre-created and are stored on the IDIS server. These rasters were created using

TINs from sounding points as described in the previous section. The python code and additional information about this process can be found in Appendix D.

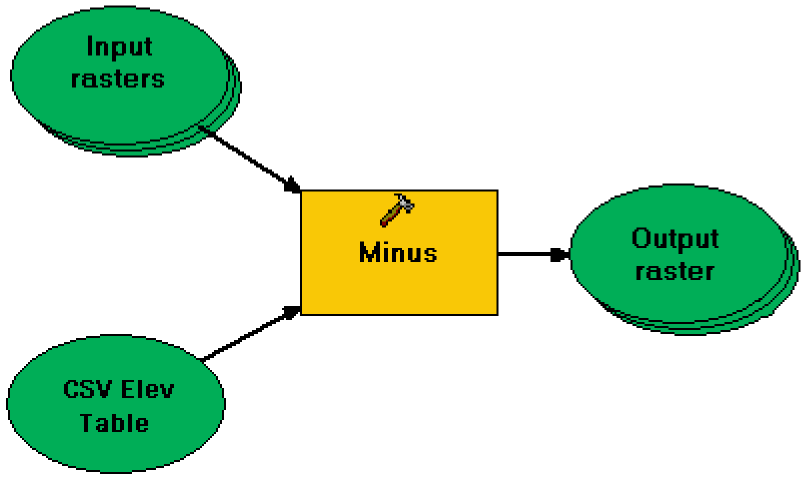


Figure 3.14: This is the tool created in Model Builder for creating rasters of reservoir depth.

Comma-Separated Values (CSV) table to a displayed table- Reservoir elevation data is downloaded daily from the NWIS website. Every morning the NWIS website posts the elevations from the previous day. The IDIS server then downloads these files in an Extensible Markup Language (XML) format (as well as a CSV) using web services. The IDIS server, through ArcGIS server manager, uses an XSLT (XML style sheet) to incorporate these files as an html table. ArcGIS then allows the new html table to be posted directly to the website application.

Web Map Service (WMS) files- WMS files are maps of spatially referenced data of geographic information. The NDMC produces files of the US Drought Monitor on a WMS file. These files can be loaded into an ArcMap document and ArcGIS Server. Without any conversion the files are loaded and projected by the server.

3.6 Web services

Once the IDIS is fully developed, it will provide data for USGS stream gauges and reservoirs monitored by the USGS and climate data from NARR. The client will be able to request data from a selected gauge or reservoir for a specified data. The data is returned using web services. Web services are also used in the scheduled task. IDIS automatically downloads data (monthly climate data and daily reservoir daily). This is accomplished using the same type of web services. The web services being developed for the IDIS are based on those developed for the Hydrologic Information System (HIS). The HIS was developed for the Consortium of Universities of the Advancement of Hydrologic Science, Inc. (CUASHI) at CRWR at UT.

These web services are designed to obtain the client requested data from the USGS NWIS website. Web services work similar to a language. Web services allow computers to access data being severed on another computer, and return data requests. A technical definition of web services is [32] :

> a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-processable format (specifically WSDL). Other systems interact with the Web service in a manner prescribed by its description using SOAP messages, typically conveyed using HTTP with an XML serialization in conjunction with other Web-related standards. [17]

Web services are the manner in which data is access from one computer (the client) accesses data from another computer (a server). The standard protocol for this the Simple Objects Access Protocol (SOAP). SOAP can be described as being similar to a language that computers are able to communicate with each other. In developing HIS, the CUASHI team created a series of standard web services, called WaterOneFlow. WaterOneFlow can obtain data from several data servers, including NWIS. The services created to obtain data are GetSiteInfo, GetVariableInfo, and GetValues. More information about this can be found at http://water.sdsc.edu/WaterOneFlow/. [33]

3.7 Scheduled Tasks

In the Windows operating system programs can be scheduled to run regularly on the computer. This operation is called a scheduled task. Tasks are typically programs that need no user input. Once the task is scheduled it runs independently at its allotted time. Tasks can be scheduled daily, weekly, monthly, when the computer starts or when a specific user logs on.

For the IDIS data requirements, there are several cases in which it is more efficient or even imperative for data to be downloaded as a scheduled task instead of through user inter-active web services. Events of major downloads require a lot of computer usage and can slowdown the server. Scheduled tasks allow downloads to occur at times when relatively few people are accessing the IDIS server. For example, refreshing the NARR data every month is a long and consuming task. Running this task causes the server to respond more slowly. The reservoir elevations are also downloaded as a scheduled task. This takes place early, every morning after USGS has posted the previous day’s elevations. The server then automatically recreates rasters showing the depths of the reservoirs and a new reservoir elevation table is posted on the IDIS website.

3.8 Technical Limitations

The integrated drought information systems are a relatively new concept. As mentioned in the literature review, to date there has been relatively little work done in developing an integrated system of data for monitoring drought. Most of the variables of drought indicators are housed by different state and national organizations. The lack of development in this area has caused obvious technical limitations. As the prototype of the Texas IDIS is being developed, the NIDIS is also being developed. So, most of the technical concepts that the IDIS is incorporating are on the cutting edge of technology. Many components of the Texas IDIS prototype are being developed uniquely for this project. Of course, the technology being developed for this project is designed with the goal to be generic enough to reproduce for future systems of a similar nature. The IDIS is still a developing tool. As its technology continues to develop, the IDIS will become more advance and efficient.

Chapter 4. Texas IDIS for the Trinity River Basin

The test area for the Texas IDIS is the Trinity River Basin. The Trinity River watershed contains 17,965 square miles (about 6% of Texas's surface area). The Trinity River itself is 715 miles long. Because the basin is so large, land types, soil type and climate vary greatly across the state. The northern portion of the watershed is covered by central Texas prairies. The dry climate of the northern portion receives only 29 inches of precipitation annually. As the river runs southeast the landscape changes from central Texas prairies, to piney woods, to Gulf Coastal prairies (which receive 53 inches of precipitation a year).[34]

4.1 The Trinity River Basin as a Prototype

TheTrinityRiver is one of the most developed watersheds in the state. The reservoirs serve the Dallas/Fortworth Metroplex and parts of Houston. The reservoirs of the basin hold more than 5000 acre-feet of water in storage. In 1955, the Trinity River Authority (TRA) was created. The TRA includes all or part of 17 counties (containing twenty percent of the state's population) along the river basin. Although the watershed falls into water management regions C and H (as well as small portions of D, G and I), the TRA has been allotted much jurisdiction over the Trinity River Basin through House Bill 20 by the 1939 Texas Legislature. The basin as well as the water management districts can be seen below in Figure 4.1. [34]

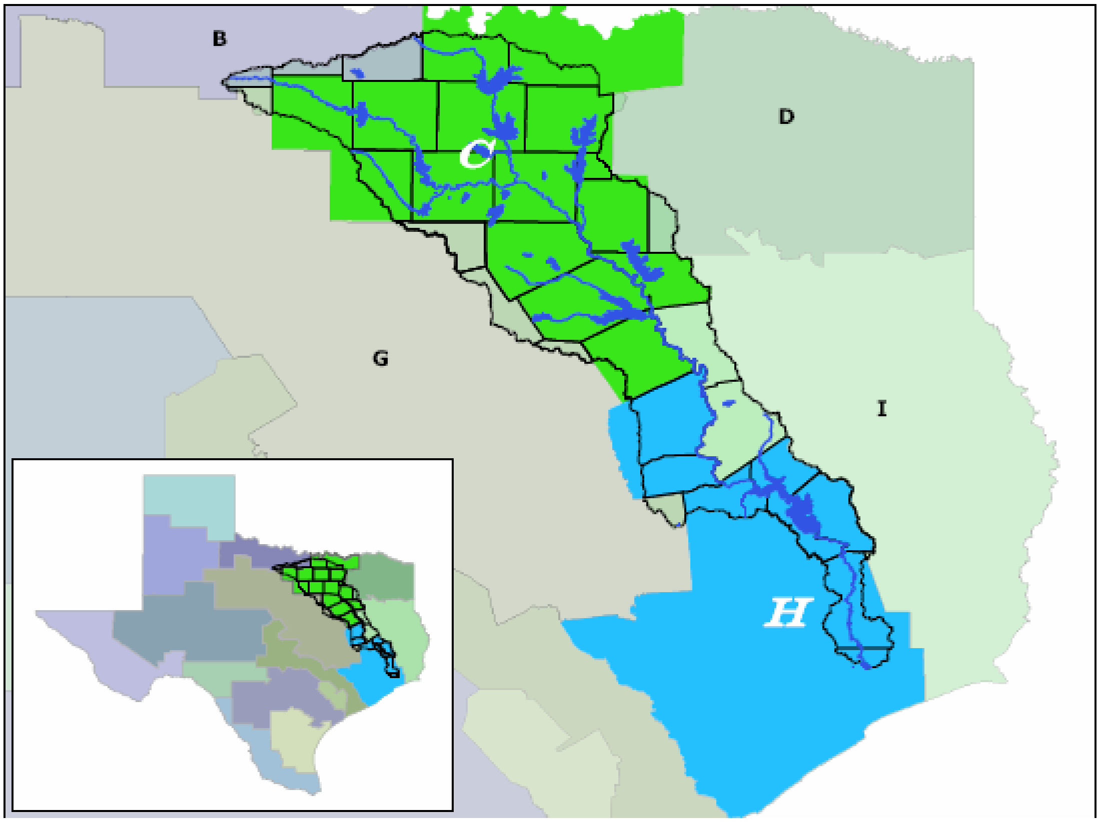


Figure 4.1: The Trinity River Basin lies within several of Texas's water management regions. As can be seen, the basin falls primarily with in region C and H. However, the Basin also contains counties that are part of region B, D, G and I. [34]

Additionally the Trinity River Basin spans over three major aquifers (Carrizo, Gulf Coast, and Trinity) and five minor aquifers (Nacatoch, Queen City, Sparta, Woodbine, Yegua Jackson). These aquifers in relation to the basin can be seen in Figure 4.2. [34]

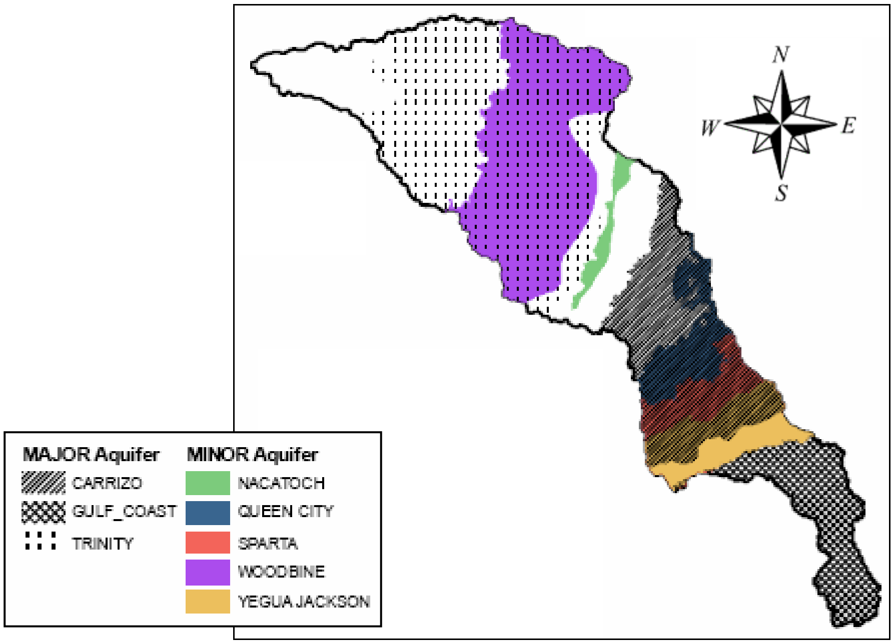


Figure 4.2: The Trinity River Basin lies over three major aquifers and five minor aquifers. [34]

The Trinity River Basin contains 30 reservoirs that serve as the water supply for the basin. The reservoirs of the Trinity River Basin supply water for approximately ten million people residing within and near the Basin. A map of existing reservoirs can be seen in Figure 4.3. In addition to the 30 current reservoirs, there are plans for an additional thirteen reservoirs to be built within the basin. [34]

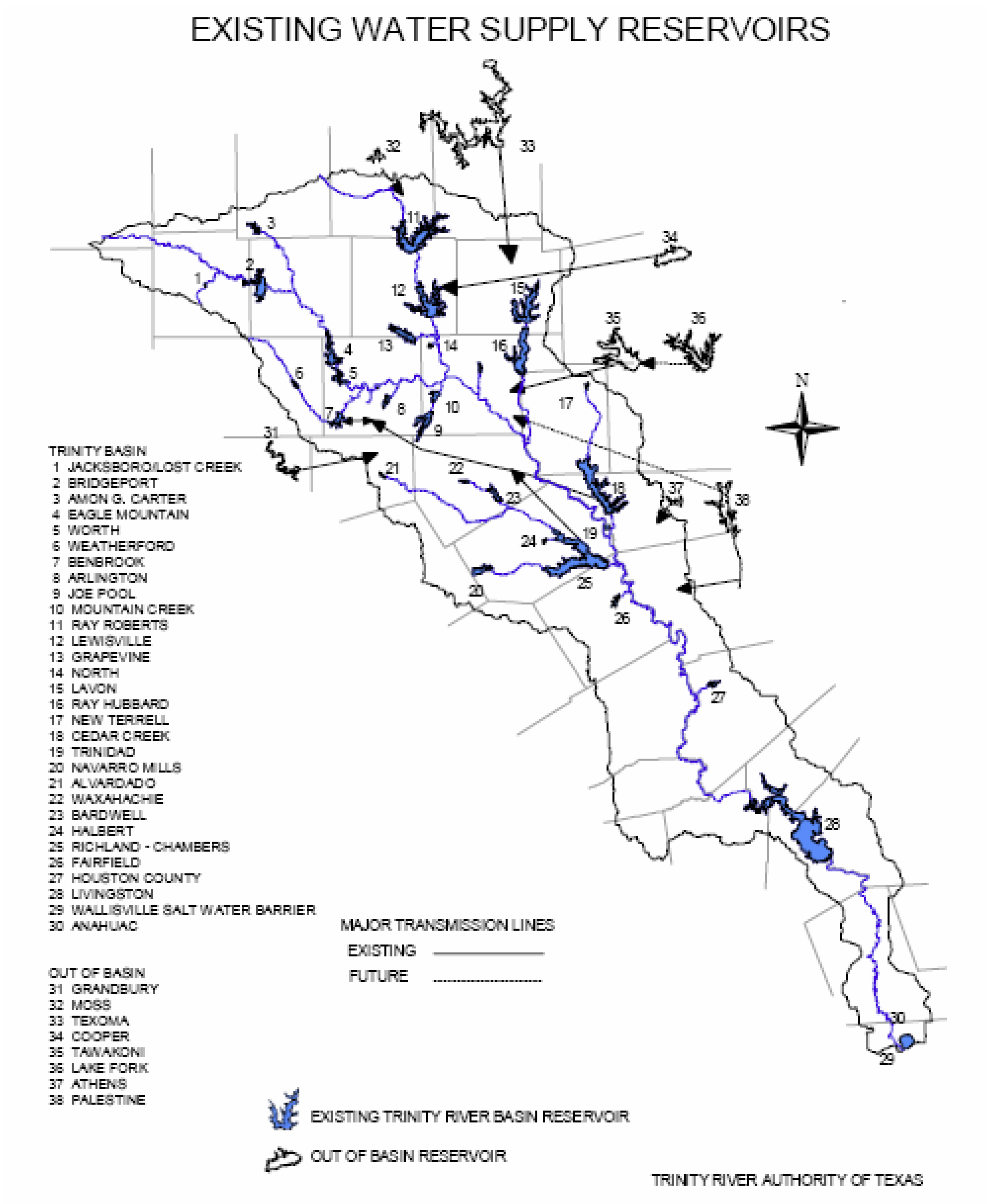


Figure 4.3: The Trinity River Basin currently contains 30 reservoirs. [34]

The surface water is important to the region. The river and its tributaries provide water for the population, industry and agriculture of the region. The region also has developed a thriving recreation industry centered around the Trinity River and its reservoirs. Table 4.1 shows the economic contributions from specific lakes. Currently

Dallas and Fort Worth are both in the stages of planning for large scale projects for developing the riverfront area of the Trinity that runs through both cities. [34]

Table 4.1: Several of the reservoirs of the Trinity River Basin have resorts or parks that make large economic contributions to the region. [34]

Reservoir	Park / Resort	Annual Economic Contribution to the Area	Jobs	In Sales Tax to Local Economies
Lake Grapevine	Gaylord Texas Resort Hotel	$450,000,000	1,700	
Lake Joe Pool	Cedar Hill State Park	$6,400,000	114	$32,000
Fairfield Lake	Fairfield State Park	$870,000	18	$4,300
Lake Livingston	Lake Livingston State Park	$5,100,000	108	$25,700

4.2 Prototype Preliminary Design

Section 3.1 described the basic design for IDIS. This section discusses the design of the IDIS prototype in the Trinity River Basin. Figure 4.4 shows the preliminary layout for the Trinity River Basin IDIS. The client accesses the server via a website. The web server stores a Hydro Basemap and drought education documents, the static data of the project. This is labeled "D" in Figure 4.4.

The web server also stores data from NARR and USGS NWIS (see labels "A" and "B"). Data from these resources is downloaded regularly using scheduled task. However, there is also another component of the IDIS that does not store data on the server, this is the data services. Data services are used to access stream gauge data and reservoir data from the USGS NWIS website. However, unlike the scheduled task this downloads data on demand for a user specified time period. "A", "B" and "C" make up the data retrieval mechanisms for the space-time data of the IDIS.

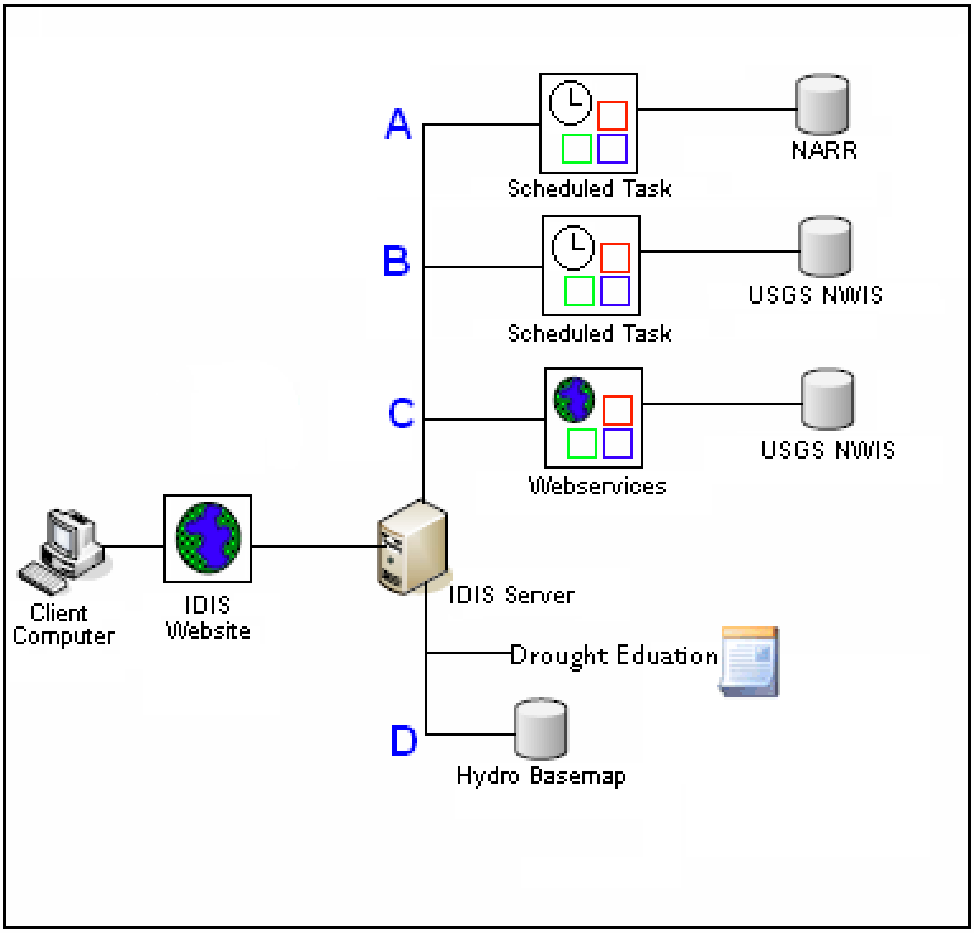


Figure 4.4: This layout represents the basic format of the IDIS prototype.

The Hydro Basemap represents features of the area that are used as a geographic reference for the space-time IDIS data. Most of the data used for the static layers is from the TNRIS StratMap. The prototype Hydro Basemap includes the feature layers: towns, cities, flowlines, roads, interstates, all water bodies, drainage basins, the Trinity River basin, and the Texas state boundaries. Figure 4.5 show the study area for the prototype and the individual feature layers that compose the Hydro Basemap.

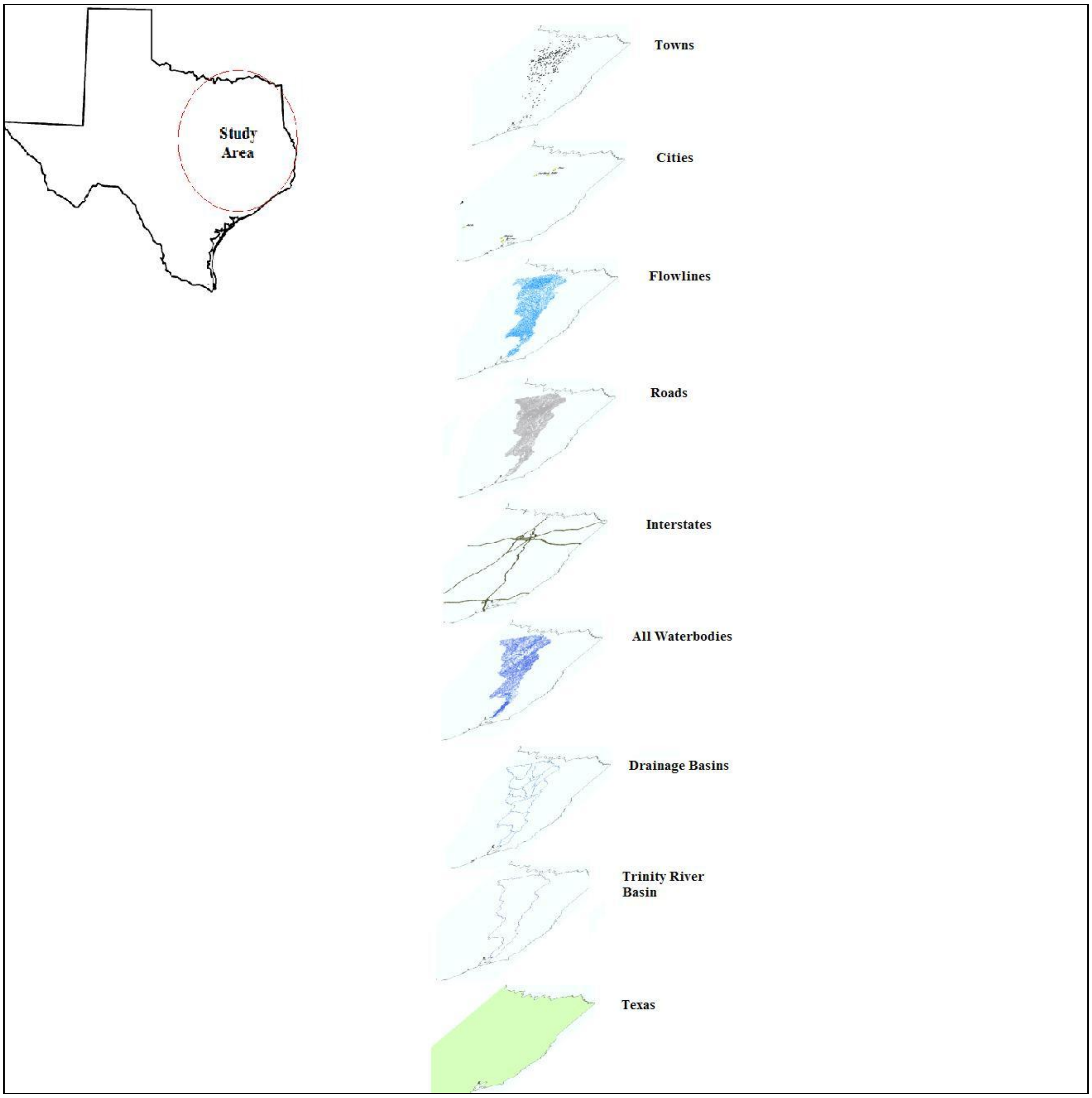


Figure 4.5: This image shows the study area and the layers that make the Hydro Basemap.

The space-time layers contain features that are linked to time series data. Figure 4.6 shows these features. The first four diagrams in the Figure show climate data linked to counties. The climate data is from NARR. More about linking this data to the counties layer can be read in section 4.4. The fifth and sixth images show stream gages and reservoirs within the Trinity River Basin. These layers are both linked to NWIS data from the USGS. The stream gauge data shows real-time stream flow data. The last layer, the raster lake catalog, is also linked to the USGS NWIS daily reservoir elevations. However, it is not linked in the same method as the rest of the space-time layers. The raster lake catalog is updated daily with raster images of reservoir depth. Details about that process can be found in sections 4.4 and 4.5.

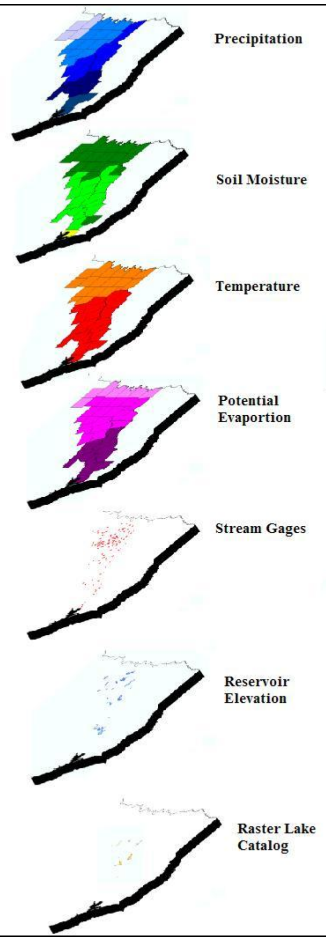


Figure 4.6: This image shows the feature layers that are associated with space-time data.

Because there are so many layers it is not feasible to view them all at once. To overcome this problem some of the layers will have limited visibility. The visibility is dictated by the scale of the map. Feature layers that more complex and detailed are not visible beyond a 1: 200,000 scale. Features that are vast are only visible above a

1:200,000. This allows the map to display all of the necessary data without becoming too cluttered. Table 4.2 describes the visibility of each feature layer.

Table 4.2: IDIS Feature Layer Visibility

Layer Name	**Visibility**
Towns	Below 1:200,000
Cities	Above 1:200,000
Stream Gages	Always
Lake Rasters	Below 1:200,000
All Flowlines	Variable Code, Identifier for TStime Tables
Rivers	Above 1:200,000
Roads	Below 1:200,000
Interstates	Above 1:200,000
Gauged Lakes	Always
All Water bodies	Below 1:200,000
Drainage Basin	Always
Trinity River Basin	Always
Counties	Always
Drought Monitor (WMS)	Above 1:200,000
Texas	Always

The IDIS website is still in development. The final version of the website will most likely resemble the image in Figure 4.7. The drought links and drought education document can be accessed through the links posted towards the top of the webpage. Tools at the top left of the screen allow the client to zoom in and out of the map and request data. The top box on the left of the screen allows the users to view the contents of the map and turn on and off layers. The next box shows a legend for the reservoir depth rasters. The following boxes, task and results, are for accomplishing the IDIS functions. The client can select a task from the task box. The results appear in the results box. The overview box provides a smaller version of the IDIS map at full extent. This tool provided the user with their location, in relation to the entire basin, when zoomed into a lake or gauge. The final box on the left side of the screen shows the reservoir levels for reservoirs within the Trinity River Basin.

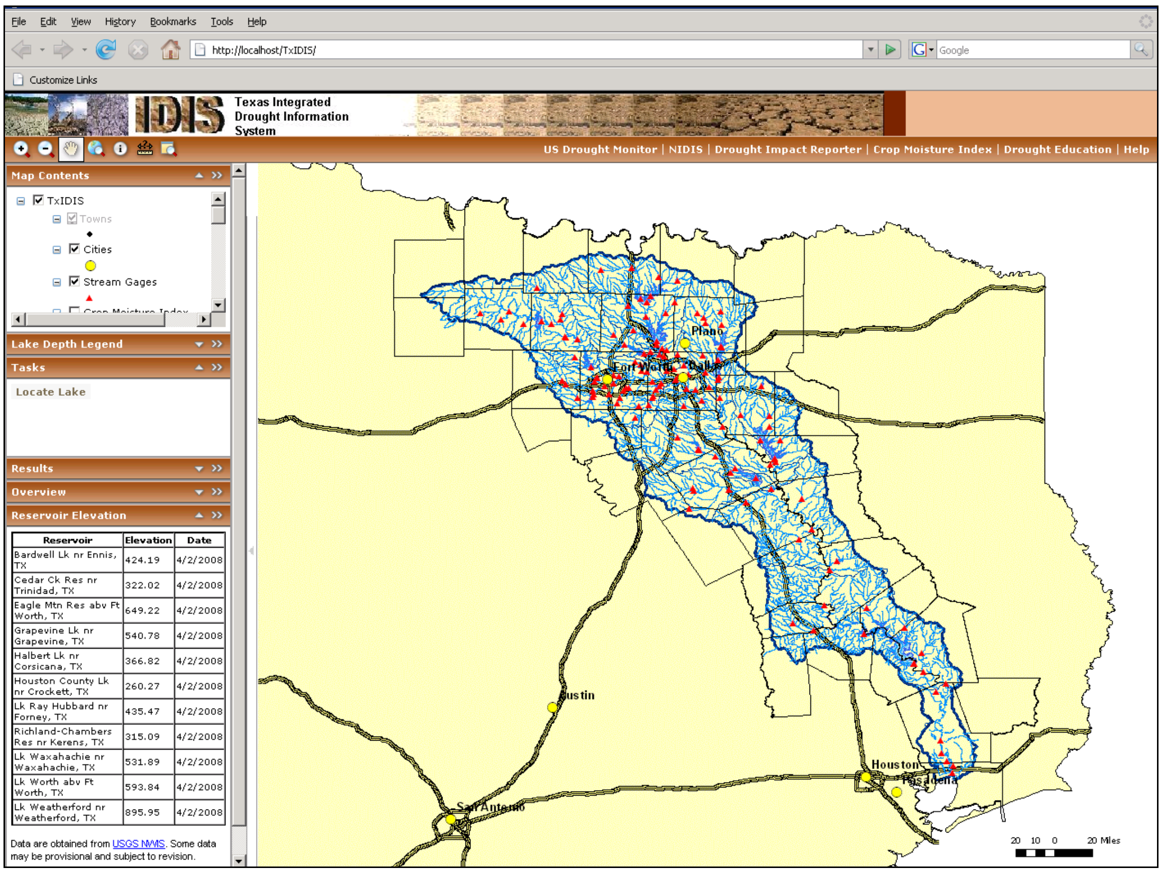


Figure 4.7: The IDIS will be accessable through a website similar to this image.

4.3 Hydrobasemap

Basemap data provides the contextual backdrop for IDIS, and includes layers such as major roads and political boundaries. This content is static, in that it is not updated over time. These layers are stored as layers in the IDIS\GISData\TXIDIS.gdb folder. These layers include:

- Towns
- Cities
- Rivers and Streams
- All Flowlines
- Roads
- Interstates
- All Water bodies
- Drainage Basins
- Trinity River Basin
- Texas

<u>Towns</u> (towns):

This layer shows all of the towns in the Trinity River Basin. It is only visible when zoomed in to a 1:200,000 scale. This is described in table 4.3.

Table 4.3: Towns Feature Layer Description

Field Name	**Field Description**
Local_ID	State Town Identifier
Name	Town Name
Population Estimate 2007	Estimated Population in 2007

<u>Cities</u> (cities):

This layer shows major cities in Texas. It is only visible when zoomed out beyond a 1:200,000 scale. This is described in table 4.4.

Table 4.4: City Feature Layer Description

Field Name	Field Description
Local_ID	State Town Identifier
Name	City Name
Population Estimate 2007	Estimated Population in 2007

All Flowlines (TRB_flowlines):

This layer shows all of the flowlines in the Trinity River Basin. It is only visible when zoomed in to a 1:200,000 scale. The feature class is created from the NHDPlus dataset. More information about the fields of this layer can be found at: http://www.horizon-systems.com/nhdplus/

Rivers (TRB_big_flowlines):

This layer shows the Rivers of the Trinity River Basin. It is only visible when zoomed out beyond a 1:200,000 scale. The feature class is created from the NHDPlus dataset. More information about the fields of this layer can be found at: http://www.horizon-systems.com/nhdplus/

Roads (TRB_roads):

This layer shows all roads with in the Trinity River Basin. It is only visible when zoomed in to a 1:200,000 scale. This is described in table 4.5.

Table 4.5: Roads Feature Layer Description

Field Name	Field Description
StratMapID	TNRIS Identifier
Shield	The Highway Shield Number for Interstates
HWY Number	The Highway Number for given to all Highways
HWY Name	Full Street Name

Interstates (interstates):

This layer shows all interstates in Texas. It is only visible when zoomed out beyond a 1:200,000 scale. This is described in table 4.6.

Table 4.6: Interstate Feature Layer Description

Field Name	Field Description
SRATMAPID	TNRIS Identifier
Prefix	The Highway Prefix
HWY Name	The Highway Number for given to all Highways
Suffix	The Highway Suffix
Direction	Direction of Interstate
Description	Description of the Segment

All Waterbodies (TRB_waterbodies):

This layer shows all of the waterbodies in the Trinity River Basin. It is only visible when zoomed in to a 1:200,000 scale. The feature class is created from the NHDPlus dataset. More information about the fields of this layer can be found at: http://www.horizon-systems.com/nhdplus/

Drainage Basins (TRB_hucs):

This layer shows the boundary of the Trinity River Basin. The feature class is created from the NHDPlus dataset. More information about the fields of this layer can be found at: http://www.horizon-systems.com/nhdplus/

Trinity River Basin (Riverbasin_boundary):

This layer shows the boundary of the Trinity River Basin. The feature class is created from the NHDPlus dataset. More information about the fields of this layer can be found at: http://www.horizon-systems.com/nhdplus/

Texas Boundary (Texas):

This layer shows the boundary of the state of Texas. This is described in table 4.7.

Table 4.7: Texas Feature Layer Description

Field Name	**Field Description**
Shape Length	Perimeter of Texas
Shape Area	Area of Texas

4.4 Space-Time Layers

Space-time data layers either change over time, or are associated with temporal data. In addition to depicting the current drought conditions in the region, some of these layers also provide a higher degree of user interaction to support further investigation into drought. The variables chosen to be represented in these layers represent the environmental shift from a meteorological drought, to an agricultural drought, to a hydrologic drought. These layers are stored in a file geodatabase named Space-time Layers in the IDIS\GISData\Space-time.gdb folder. These layers include:

- Counties

- Stream Gages
- Gaged Lakes

There are also tables in this geodatabase that describe the dynamic aspects of the Space-time layers. These tables include:

- TSTable Climate
- TSTable Streams
- TSTable Lakes

There are also tables in this geodatabase that provide statistics for the Counties and Stream Gages layers. The statistics for climates are based on NARR 30 year average, and are determined for each county. The statistics for the streams are from the National Hydrography Dataset (NHDPlus). These statistics are useful for identifying anomalies in current conditions by comparing current time series values with historical ones. These tables include:

- Climate Statistics
- Stream Statistics

Additionally, another aspect of the geodatabase is the data catalogs. There are two types of data catalogs: raster catalogs and dynamic variable tables.
The Space-time datasets are described below.

<u>Counties</u> (NARR_counties):
This layer shows counties. Counties are associated with climate time series data retrieved from NARR. By clicking on a county in the map, the user can bring up a time series graph for a given climate variable, spatially averaged over the county. Each county is identified with a HydroID. The HydroID is used to associate the counties with NARR climate data stored in TSTable Climate. The FeatureID from TSTable Climate matches the HydroID in the Counties layer. For anomaly calculations the Climate Statistics table is used. The link between this table and the Counties layer is established in the same method as the TSTable Climate link. This is described in table 4.8.

Table 4.8: Counties Feature Layer Description.

Field Name	Field Description
HydroID	Unique numerical identifier for the county
NAME	The name of the county
Climate Region	The NOAA Climate Region Identifier

Stream Gauges (Stream_gages):

This layer shows USGS stream gages within the Trinity River Basin. Gauges are associated with USGS time series stream gauge data. Each gage is identified with a HydroID that is equal to the USGS gauge ID number. The HydroID is used to associate the gage with the stream flow time series data stored in TSTable Streams. The FeatureID from TS Streams matches the HydroID in the Stream Gages layer. For anomaly calculations the Stream Statistics table is used. The link between this table and the Stream layer is established in the same method as the TSTable Stream link. The feature class is created from the NHDPlus dataset. More information about the fields of this layer can be found at: http://www.horizon-systems.com/nhdplus/.

Gauged Lakes(Gaged_lakes):

This layer shows lakes that are gauged by the USGS within the Trinity River Basin. Lakes are associated with USGS time series reservoir gage data. By clicking on a lake in the map, the user can bring up a time series graph for daily reservoir elevation at a given lake. Each lake is identified with a HydroID that is equal to the USGS gage ID number. The HydroID is used to associate the lake with the reservoir elevation time series data stored in TSTable Lakes. The FeatureID from TS Lakes matches the HydroID in the Gauged Lakes layer. For anomaly calculations the Lake Statistics table is used. The link between this table and the Gauged Lakes layer is established in the same manner as the TSTable Stream link. The feature class is created from the NHDPlus dataset. More information about the fields of this layer can be found at: http://www.horizon-systems.com/nhdplus/. One of the fields contained in the attribute table is the conservation pool elevation. This field is used to calculate reservoir fullness. These values are used similar to the statistics tables for Stream Statistics and Climate Statistics.

TSTable Climate (TSTable_climate):

This table shows data from the North American Regional Reanalysis (NARR). This table is reloaded once a month, and is populated by a time series of climate data, in monthly time steps. The climate data is divided into the seven climate variables that have been downloaded. Every month the data is refreshed with additional data information from the most recent month. NARR data is downloaded in NetCDF form and then converted to a table using a variety of GIS processing tools. This data can then be associated with the Counties layer and Climate Statistics table through the HydroID/FeatureID link. This is described in table 4.9.

Table 4.9: Time Series Fields Table for Climate Variables

Field Name	Field Description
FeatureID	Links to HydroID
TSTime	Date (Monthly Time Stamp)
VID30	Potential Evaporation TSValue
VID40	Precipitation TSValue
VID50	Soil Moisture TSValue
VID60	Temperature TSValue
VID70	Subsurface Runoff TSValue
VID80	Non-infiltrating Surface Runoff TSValue
VID90	Evaporation TSValue

TSTable Streams (TSTable_stream):

This table shows time series data downloaded from USGS NWIS website for stream gages. The data provided is real time data. This table is populated using web services to harvest data from the NWIS website. The user provides the service with the desired gages and time span. The time series table will contain FeatureID (which links to the HydroID of the Stream Gage layer), TSTime, and a time series value (this is defined by the Variable Code). This is described in table 4.10.

Table 4.10: Time Series Fields Table for Stream Gauges

Field Name	Field Description
FeatureID	Links to HydroID
TSTime	Date (Realtime)
VID20	Stream Gage TSValue (from NWIS)

TSTable Lakes (TSTable_lakes):

This table shows time series data downloaded from USGS NWIS website for reservoirs. The data provided is daily average data. This table is populated using web services to harvest data from the NWIS website. The user provides the service with the desired lake and time span. The time series table contains FeatureID (which links to the HydroID of the Gaged Lakes layer), TSTime, and a time series value (this is defined by the Variable Code). This is described in table 4.11.

Table 4.11: Time Series Fields Table for Reservoirs

Field Name	Field Description
FeatureID	Links to HydroID
TSTime	Date (Daily Time Stamp)
VID10	Reservoir Elevation TSValue (from NWIS)

Climate Statistics (ClimateStat):

This table stores the average values for each county by month of year for the four climate variables used in this project: soil moisture, precipitation, temperature and potential evaporation. For each month, the average value is derived from 30 years of the NARR values. For example, 30 years of data for the month of January are used to compute the average value that one expects to see in January. This table is used for presenting current data as an anomaly value. This is described in table 4.12.

Table 4.12: Climate Statistics Table

Field Name	**Field Description**
NAME	County Name
(3 character month abbreviation)_VID30	NARR Monthly 30 Year Average for Potential Evaporation
(3 character month abbreviation)_VID40	NARR Monthly 30 Year Average for Total Precipitation
(3 character month abbreviation)_VID50	NARR Monthly 30 Year Average for Soil Moisture
(3 character month abbreviation)_VID60	NARR Monthly 30 Year Average for Temperature
(3 character month abbreviation)_VID70	NARR Monthly 30 Year Average for Subsurface Runoff
(3 character month abbreviation)_VID80	NARR Monthly 30 Year Average for Non-infiltrating Surface Runoff
(3 character month abbreviation)_VID90	NARR Monthly 30 Year Average for Evaporation
FeatureID	Unique Identifier for the Feature

<u>Stream Statistics</u> (StreamStat):

This table shows the statistics for each stream gage. These values are established from the National Hydrography Dataset. This table is used for presenting current data as an anomaly value. This is described in table 4.13.

Table 4.13: Stream Statistics Table

Field Name	Field Description
Station_NM	Gage Station Name
Min	Minimum Flow
P1, P5, P10, P20, P25, P30, P40, P50, P60, P70, P80, P90, P95, P99	Percentile of flow
Max_	Maximum Value
AVE	Average
STD	Standard Deviation
FeatureID	Unique Identifier for the Feature

*A lake average table does not exist because lake elevation statistics are based on the conservation pool elevation.

Lake Rasters (raster_lakes);
The raster catalog is used to index the depth raster of the lakes of the Trinity River Basin. New rasters displaying the depth of reservoirs are created daily through scheduled tasks. The raster catalog is used as an archive.

Dynamic Variables (Dynamic_variables);
This table describes variables that change through time and is used in Time Series tables. This is described in table 4.14.

Table 4.14: Dynamic Variables Table

Field Name	Field Description
VariableID	Unique Numerical Identifier of the Variable
VarName	Variable Name
VarCode	Variable Code, Identifier for TStime Tables
VarUnits	Units of Measurement
VarDesc	Variable Description

4.5 Functions

The functions of IDIS bring the system full-circle. Through the functions users are able to access the drought data they need. The design goals of these tasks is to develop systems by which users can easily access drought related information, make comparisons between drought variables and look at anomalies in the data over a period of time. By enabling these tasks for users, users are able to gain a better, more complex comprehension of actual drought events in the Trinity River Basin. Currently, the IDIS is still in development, therefore not all of the functions have been completely programmed. However, the following describes the tasks that the IDIS can currently achieve, and the tasks that the IDIS will be able to achieve upon its completion.

Functions Developed

Reservoir Table- Everyday the reservoir elevations for the previous day are downloaded from NWIS using web services and scheduled tasks described in sections 3.6 and 3.7. The web service returns an XML file that is then converted to an html file. The conversion is managed by an XLST style sheet through ArcGIS server manager. Once the reservoir table is in html format it can be viewed on the IDIS webpage.

Reservoir Depth Rasters- Every day the reservoir elevations for the previous day are downloaded from NWIS using web services and scheduled tasks described in sections 3.6 and 3.7. The web service returns a CSV file of the reservoir elevations. IDIS contains a scheduled task python code that uses the CSV file elevation values in a raster math tool to create rasters of the current reservoir depth. The elevations are subtracted from a raster displaying the bathymetry of the lake. The reservoir bathymetry file is created by making a raster of the reservoir TIN. More detailed information about this can be found in sections 3.3.

Functions in Development but Not Yet Complete

Climate Data Graphs and Tables- One of the functions currently in development for the IDIS is the climate variable data retrieval. Through this tool the user will be able to download climate data as a table or view graphs of the data in relation to time. The following steps describe the process this tool will go through to return climate data to the client.

1. User clicks on the county> county is selected
    - The county file contains county name, Hydro ID, average soil moisture, average precipitation, average temperature and average potential evaporation (area, and x and y centroids are also fields for the counties files, but they don't play a role in this procedure)
2. User is prompted for parameters and date
    - The parameters are soil moisture, precipitation, temperature, and potential evaporation
    - User chooses desired format for data:
        - download files (showing date and climate variables values)
        - graph showing values over time compared to normal
        - graph showing percent from normal
3. Parameters and date range are inputted for desired parameters and date range

4. The server accesses tables of data containing the climate variable data and/or the anomaly data (the development of the climate data tables is discussed in section 3.5 and 4.4).
5. Depending on the user's choice:
    - A table is can be downloaded by the user (this is accomplished by using caching)
    - Table is made to a graph
        - The code for creating the graphs is similar to the code using in the CUASHI HIS.
        - Graphs are returned
            - percent normal vs. time
            - actual value vs. time

Stream Flow Graphs and Tables- The IDIS also allows users to access stream data as a downloadable table or as a graphs. The user can zoom into (at least 1:200000) an area on the map to see all of the flowlines in the Trinity River Basin. Once zoomed in the user can select a section of stream gauge. Once the stream is selected the user will be prompted for a time span. Data will be collected for that stream section from the USGS NWIS and returned to the user as a downloadable table, a viewable graph of actual values, or a viewable graph of values as a percent of major stage flow (or typical flow). The data will be downloaded from: http://waterdata.usgs.gov/tx/nwis/current?type=flow&group_key=basin_cd&search_site_no_station_nm=Trinity#top_of_page. The framework for accomplishing this task is as follows:

- Files used for the stream gauges: points based on USGS latitude and longitude, appended to include USGS #. This file also includes average flow values for each particular gauge.
- User selects a stream gauge

    - User is prompted for a time span
    - User choose to download a table or view a graph
- Selected stream gauge field is exported with the time span to a new table
- Web services uses new table to obtain data from USGS NWIS
- Data is returned and appended to the table
    - Field Calculator is used to find the % of stage flow for a stream
- User can be returned a table if chosen initially
- Table is transformed to XY data
- Event data is exported to create a feature
- User is returned a graph if chosen initially
    - percent of stage vs. time
    - Actual stream flow values vs. time

Reservoir Data- Reservoir* data can also be accessed by zooming in to the map (at least 1:200000). Once the user has zoomed in they will be able to view lake access points and lake depth (more about this can be read in the first portion of this section, under depth raster). Additionally, the user can retrieve lake elevation data over time by selecting the reservoir. Using web services, the server will obtain lake elevation from USGS NWIS and report it back to the user as a downloadable table, a viewable graph of actual values or a viewable graph of the reservoir percent full (as compared to the conservation pool). This data will be downloaded from: http://waterdata.usgs.gov/tx/nwis/current/?type=lake&group_key=basin_cd. The steps to accomplish this task are as follows:

- Files used for the Reservoir: NHD appended to include USGS #, latitude and longitude values for a point within each reservoir, and conservation pool elevation
- User selects a reservoir and zooms to reservoir
    - User is prompted for a time span
    - User choose to download a table or view a graph
- Selected reservoir field is exported with the time span to a new table
- Web services uses new table to obtain data from USGS NWIS
- Data is returned and appended to the table
    - Field Calculator is used to find the % full of the reservoir
- User can be returned a table if chosen initially
- Table is transformed to XY data
- Event data is exported to create a feature
- User is returned a graph if chosen initially
    - % of stage vs. time
    - Actual stream flow values vs. time

*Reservoirs with Data to be used:

Lake Arlington

Trigg Lake

Joe Pool Lake

Mountain Creek Lake

Ray Roberts Lake

Lewisville Lake

Grapevine Lake

Lavon Lake

Lake Ray Hubbard

New Terrell City Lake

Cedar Creek Reservoir

Navarro Mills Lake

Lake Waxahachie

Bardwell Lake

Halbert Lake

Lost Creek Reservoir

Bridgeport Reservoir

Lake Worth

Eagle Mountain Reservoir

Lake Weatherford

Benbrook Lake

Richland-Chambers Reservoir

Houston County Lake

Livingston Reservoir

4.6 Future Work

The IDIS is still in development, and will mostly likely to continue to be developed over a long period of time. As mentioned in the literature review (section 2.5), the technology for systems like the IDIS is relatively new. As the Trinity River Basin IDIS continues to be developed other systems continue to be developed (such as the NIDIS), the technology will increase giving way to a more dynamic and useful IDIS. The previous section mentioned task for this prototype still being constructed. These are a priority for the prototype system. However, there are additional secondary tasks that would propel the IDIS further in its goals. The additional future work is listed below.

<u>Incorporation of Additional Data Sources</u>- More and more data resources are being developed and are being made available online. As internet services and web services continue to develop incorporating these features will become a possibility. Some of the additional data sources that could included in the IDIS are vegetation stress related

remote sensing data, improved precipitation data, atmospheric cycle data (from ENSO and TOA) land cover and land change data. As more and more data becomes accessible to IDIS it should be incorporated based on its usefulness to the system as a whole.

<u>Bathymetry Interpolation</u>- The TWDB is in the process of developing a method for improving lake bathymetry. This process is being developed by Dr. Jordan Furnans. When the TIN of a reservoir is generated it creates a contour bubbling affect around the boundaries of the reservoir. This is due to the process used in TIN development, which is based on the points closest to a sounding point. By interpolating between the sounding points of the reservoir survey a better estimate of the lake bathymetry can be provided. This gives an improved bathymetry for the reservoir, particularly near the shoreline. It also allows for a better estimate of the amount of water in a reservoir. This was tested successfully on Grapevine. As this process is developed it would be useful to apply it to lakes featured in the IDIS.

<u>Animation of Rasters</u>- The IDIS is currently designed to display only rasters that are current. In the future, as ArcGIS is developed further it would be useful to incorporate the ability to animate raster through time. With this capability the IDIS could show the fluctuations in the US Drought Monitor, Corp Moisture Index and Drought Impact report (as well as any raster data that might be incorporated to IDIS in the future). Viewing the fluctuations of this data through time will allow users to compare drought indices with climate and hydrologic data overtime.

<u>Animation of Features</u>- Animating the features of IDIS could also be a useful tool for drought visualization.

Chapter 5. Conclusions

Drought is a persistent and costly problem for all communities. Texas is no exception. Droughts in Texas have costly impacts environmentally, socially and economically. However, the complex definition of drought and its dynamic nature makes it a difficult problem to mitigate. There is no clear definition of when a drought begins or when a drought ends, Characteristics of drought vary from region to region. Droughts occur in three consecutive stages. First a meteorological drought occurs, in which there is a decrease in precipitation. This propagates to an agricultural drought, in which soil moisture decreases. Finally, the drought progresses to a hydrologic drought, in which surface water availability is impacted by the drought conditions. The multiple dimensions of drought make it difficult to characterize, and even harder to mitigate. The IDIS aims to serve as a tool for decision makers, researchers and the general public. Its primary focus is to improve the understanding of drought events and drought conditions by allowing integrated several dimensions of drought related observational data.

Ultimately, the IDIS will be a tool for public information. The IDIS is a server that provides drought education information, hosts drought related data, hosts geographic data (the Hydro Basemap), and uses web services to obtain data from other sources. The drought education portion of the IDIS provides links to educational drought documents and websites that relate drought information. The main aspect of the IDIS is the geographic information component. The server uses ArcGIS as a tool for visualizing the data and data integration.

The geographic information system portion of the IDIS can be divided into two major portions: static and dynamic. The static information is contained within a Hydro Basemap. The Hydro Basemap serves as a reference for drought information. The features class layers of the Hydro Basemap include political boundaries, roads and hydrologic features. The hydrologic features come from the NHDPlus. The purpose of the Hydro Basemap is to create a backdrop to the dynamic drought information. The Basemap itself contains no drought related information.

The dynamic features, or space-time layers, are joined to drought data. The space-time layers are contained within a single geodatabase comprised of feature layer classes, time series data tables, and variable information tables. The information contained within the layers of the space-time geodatabase allows the layers to be associated with temporal drought information. The data joined to the space-time layers depicts current drought conditions for the region. Some of the layers allow for user interactive investigation into drought. The data sources and data variables were chosen to represent the environmental shift from a meteorological drought, to an agricultural drought, to a hydrologic drought. Accessing data from disparate sources gives a full view of the current stage of drought, and how it propagates through time.

The drought information is obtained from data servers around the country. The datasets accessed by the IDIS include hydrologic data from NWIS, climate data from NARR and drought indices from the Drought Monitor. These datasets where chosen because they describe the different stages of drought intensity. The information may come in as either an xml table or a raster image. The IDIS intakes these forms of data and integrates them into a similar format so that they may be attached to a geographic feature and accessed by a user. This is accomplished through a system of unique identifiers that link data to features. All space-time features have a HydroID that allows them to be linked to data sources by their unique identifiers, FeatureIDs. For instance, NWIS uses unique identification number for all gauges. IDIS refers to these numbers as the Feature IDs. The gauges within the gauge space-time layer are also given an identifier, a HydroCode. The HydroCode of a gauge matches the FeatureID with the NWIS data, allowing the NWIS gauge data to be matched with its corresponding feature on the map. The IDIS integrates data from several formats. These formats include WMS files, NetCDF and XML tables.

The IDIS server uses web services to obtain data from other data servers around the country. The two methods employed by the IDIS web services are: as prompted from the user and as a regularly scheduled task. User prompted web services have the ability to retrieve data quickly. The user is asked to input data to specify their request--

such as time period and variable. User prompted web services are compatible for accessing NWIS data. Access to NARR data and US Drought Monitor data is more complex. This data is automatically and regularly, downloaded by a program. The program functions as a scheduled task. Through this task the data is obtained and integrated without user interaction. These tasks typically take place during the early morning, when user activity is at the lowest.

The Texas IDIS prototype for the Trinity River Basin is still in development. There are programming obstacles to yet to be overcome. Additionally, improvement to the IDIS will be an on-going effort as the technology evolves and more data is available. However, the work that has been accomplished to this point has created a structure on which future integrated drought information systems can be based. The current prototype establishes a format for which users can access data from several resources to analyze drought conditions over time. In time the IDIS has the potential to be a useful tool for decision makers, the public and researchers.

As the IDIS continues to develop, it will become progressively more useful. Its next stage of development will likely involve the completion of the functions mentioned in section 4.5. Once the graphing tasks are able to be included in the IDIS, the user's ability to analyze drought status and drought propagation will be greatly increased. The work outlined in section 4.6 will also increase the usefulness of IDIS as a tool. Adding additional data sources will allow the user to obtain a thorough comprehension of drought impacts. The bathymetry interpolation techniques will be an aid to residences, boats, and waterside business owners, since the improved techniques will allow users to view more accurate estimates of reservoir depth.

Finally, the animation of rasters and features is integral to the IDIS long-term development. The graphing feature is a useful tool. However, graphs can sometimes be deceiving or difficult to comprehend, particular for someone not working in a science-related field. Animations offer an effective visual display, which will help IDIS clients to gain a full understanding of the drought situation.

Provided data maintenance and effective program updates, the IDIS will be a useful tool for the state of Texas. It will be applicable for decision makers, researchers and the public at large. Today, with the allowances of technology, the IDIS is able to integrate disparate data from data servers around the US. This creates a more accurate image of drought through combining hydrologic data and climate data, as well as drought indices. With a tool like this decisions makers, planners and researchers may be able to make further headway in the battle to mitigate drought.

Appendices

Appendix A

List of Abbreviations

IDIS	Integrated Drought Information System
TNRIS	Texas Natural Resource Information System
CRWR	Center of Research in Water Resources
UT	University of Texas - Austin
TWDB	Texas Water Development Board
ESRI	Environmental Systems Research Institute, Inc.
GIS	Geographic Information System
USGS	United States Geographic Survey
NWIS	National Water Information System
NOAA	National Oceanic Atmospheric Administration
NCEP	National Centers for Environmental Prediction
NARR	North American Regional Reanalysis
CPC	Climate Prediction Center
CMI	Crop Moisture Index
NDMC	National Drought Mitigation Center
NHDPlus	National Hydrography Dataset Plus
StratMap	Strategic Mapping Program
WMS	Windows Mapping Service
NIDIS	National Integrated Drought Information System
FEMA	Federal Emergency Mapping Agency
ENSO	El Nino / Southern Oscillation
NESDIS	National Environmental Satellite, Data Information Service
TOGA	Tropical Ocean Global Atmosphere
NAO	North Atlantic Oscillation
IPCC	Intergovernmental Panel on Climate Change

PDSI	Palmer Drought Severity Index
NCDC	National Climate Data Center
NDPC	National Drought Policy Commission
DPC	Drought Preparedness Council
SPI	Standard Precipitation Index
KBDI	Keetch-Byram Drought Index
TFS	Texas Forestry Service
VT	Vegetation and Temperature Condition Index
TAEX	Texas Agricultural Extension Service
TDA	Texas Department of Agriculture
USDA	U.S. Department of Agriculture
TCEQ	Texas Commission on Environmental Quality
WMO	World Meteorological Organization
NADM	North American Drought Monitor
NHD	National Hydrography Dataset
NHDPlus	National Hydrography Dataset Plus
EPA	Environmental Protection Agency
NED	National Elevation Dataset
NLCD	National Land Cover Dataset
GPS	Global Positioning System
DGPS	Differential Global Positioning System
TIN	Triangulated Irregular Network
NOMADS	National Operational Model Archive and Distribution System
THREDDS	Thematic Real-time Environmental Distribution Data Service
TDS	THREDDS Data Server
UTC	Coordinated Universal Time
NWISW	National Water Information System Website
NetCDF	Network Common Data Form
UCAR	University Corporation for Atmospheric Research

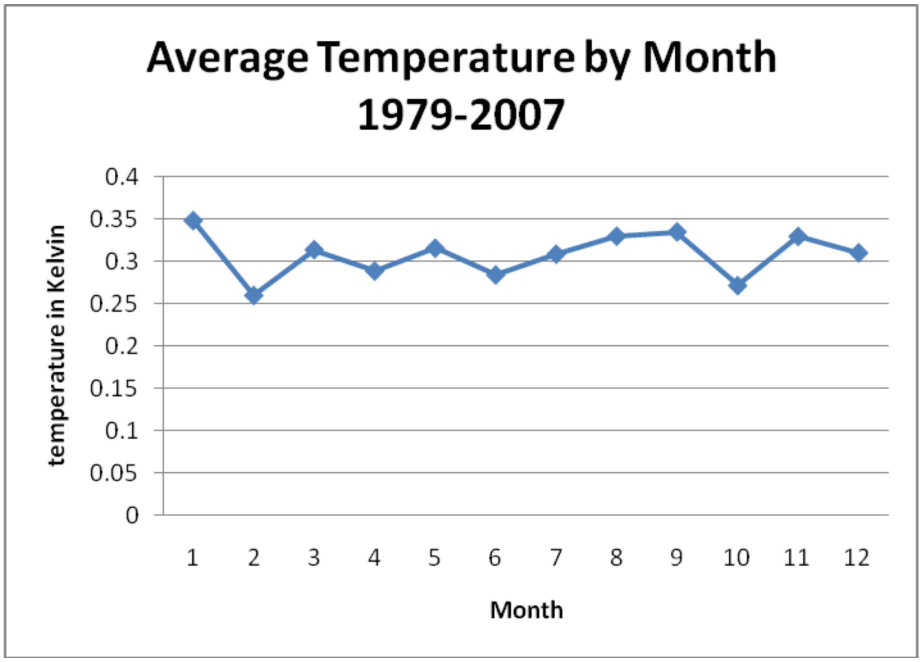
CSV	Comma Separated Values
XML	Extensible Markup Language
XSLT	XML Style Sheet
HIS	Hydrologic Information System
CUASHI	Consortium of Universities of the Advancement of Hydrologic Science, Inc.
SOAP	Simple Object Access Protocol
TRA	Trinity River Authority

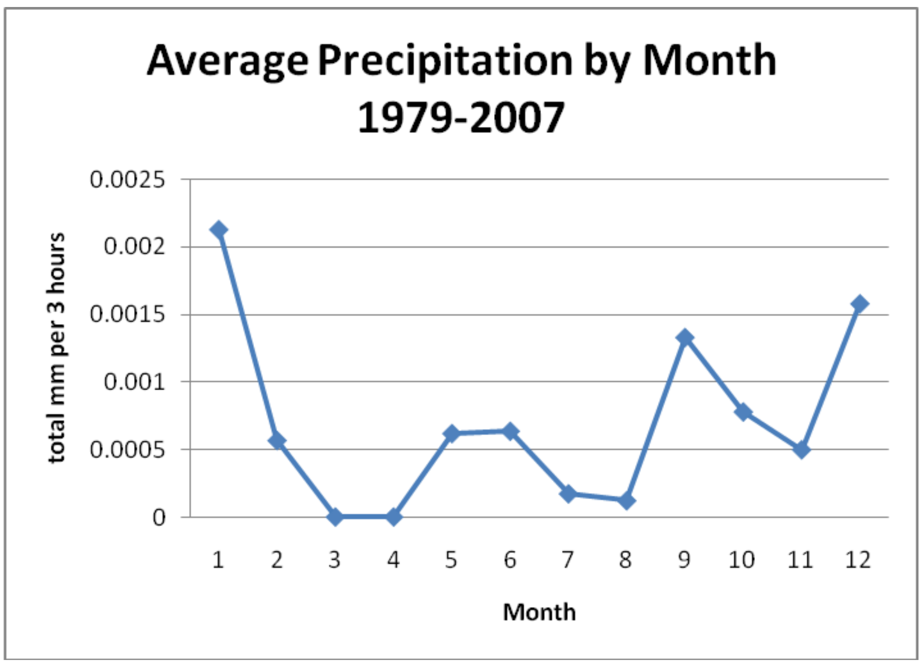
Appendix B

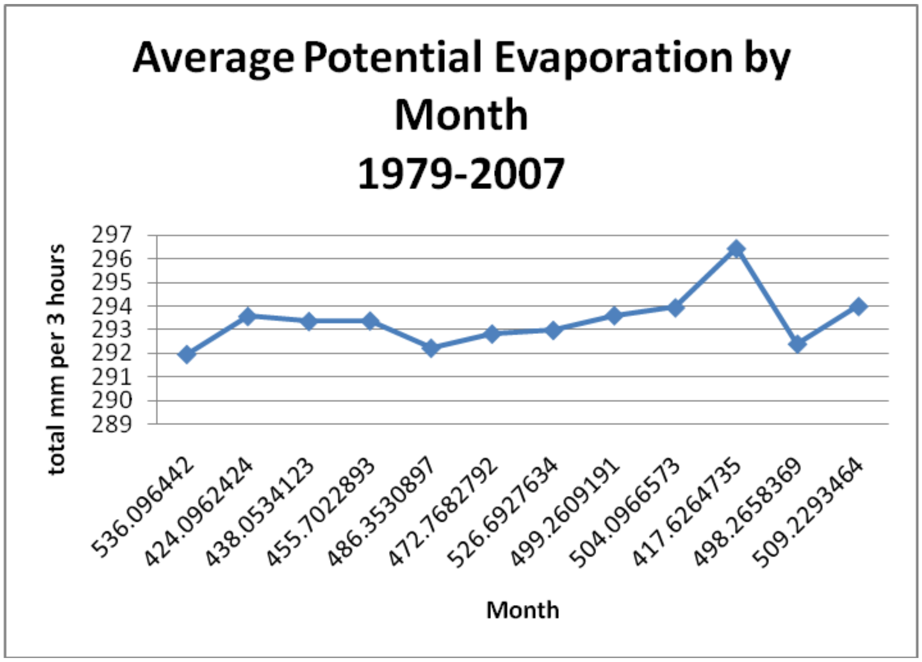
NARR Data							
	Potential Evaporation (mm/3hrs)	**Evaporation (mm/3hrs)**	**Precipitation (mm/3hrs)**	**Soil Moisture (mm in the top 100cm)**	**Subsurface Runoff (mm/3hrs)**	**Surface Runoff (mm/3hrs)**	**Temperature K**
Average	0.756829117	0.30921763	0.354108022	506.4666351	0.001709882	0.019119473	293.468674
Standard Deviation	0.325762707	0.177333186	0.234286005	104.3723073	0.012816353	0.02443026	7.265588735
Minimum	-0.00718313	-0.01615720056	4.86409E-05	242.5140076	0.00000000000	0.00000000000	274.4129944
Median	0.759895504	0.26535549760	0.312595502	497.769989	0.00000000000	0.00781250000	294.1730042
Max	1.718330026	1.14924001694	1.929720044	1000.01001	0.35937500000	0.25000000000	307.2850037
1st Quartile	0.463270999	0.162100002	0.180040002	435.6715012	0	0	287.1640015
2nd Quartile	0.759895504	0.265355498	0.312595502	497.769989	0	0.0078125	294.1730042
3rd Quartile	0.985358	0.45617874	0.48489251	575.1767426	0	0.0234375	300.1262589
4th Quartile	1.718330026	1.149240017	1.929720044	1000.01001	0.359375	0.25	307.2850037

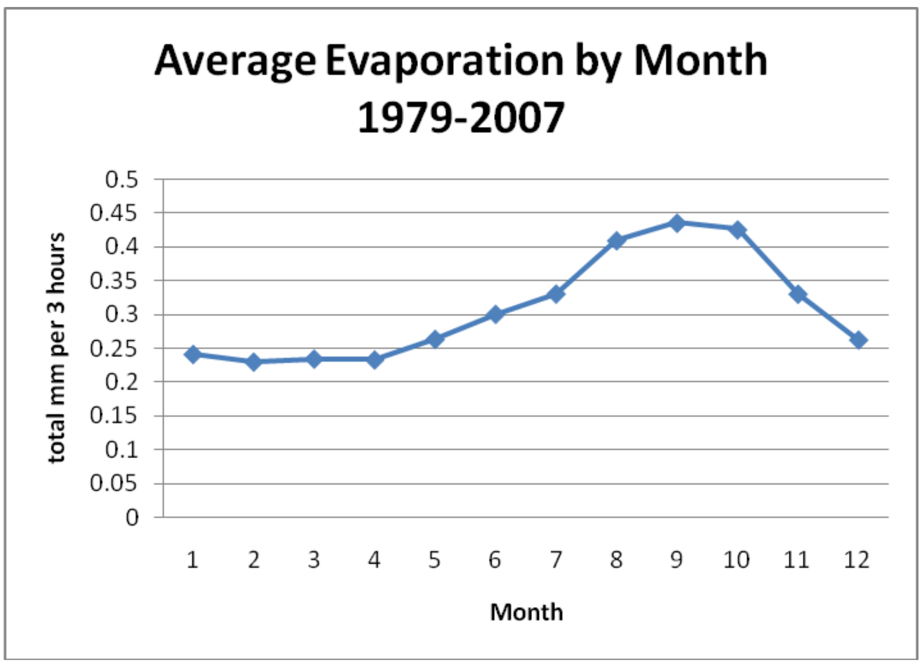
NARR by Month							
Month	**Potential Evaporation (mm/3hrs)**	**Evaporation (mm/3hrs)**	**Precipitation (mm/3hrs)**	**Soil Moisture (mm in the top 100cm)**	**Subsurface Runoff (mm/3hrs)**	**Surface Runoff (mm/3hrs)**	**Temperature K**
1	0.35	0.24128836	0.31	549.41	0.000242305	0.012342869	283.00
2	0.45	0.229924291	0.38	575.23	0.000587406	0.019443143	284.94
3	0.63	0.234356521	0.36	583.53	0.000815026	0.017901202	289.05
4	0.85	0.233075547	0.32	551.23	0.001269	0.013250057	293.22
5	0.98	0.26347091	0.49	519.76	0.001651827	0.022147237	297.54
6	1.07	0.300639653	0.46	500.04	0.00382827	0.022608049	300.67
7	1.19	0.330810872	0.27	462.84	0.007493485	0.019155519	302.42
8	1.14	0.409654071	0.24	437.64	0.002254424	0.018871944	302.74
9	0.91	0.435647649	0.31	440.07	0.001481682	0.02686168	299.61
10	0.69	0.425748504	0.39	453.15	0.000404095	0.029449313	294.63
11	0.47	0.330584375	0.37	487.69	0.000248129	0.013455649	288.73
12	0.32	0.262569093	0.34	524.12	6.60832E-05	0.013275378	283.93

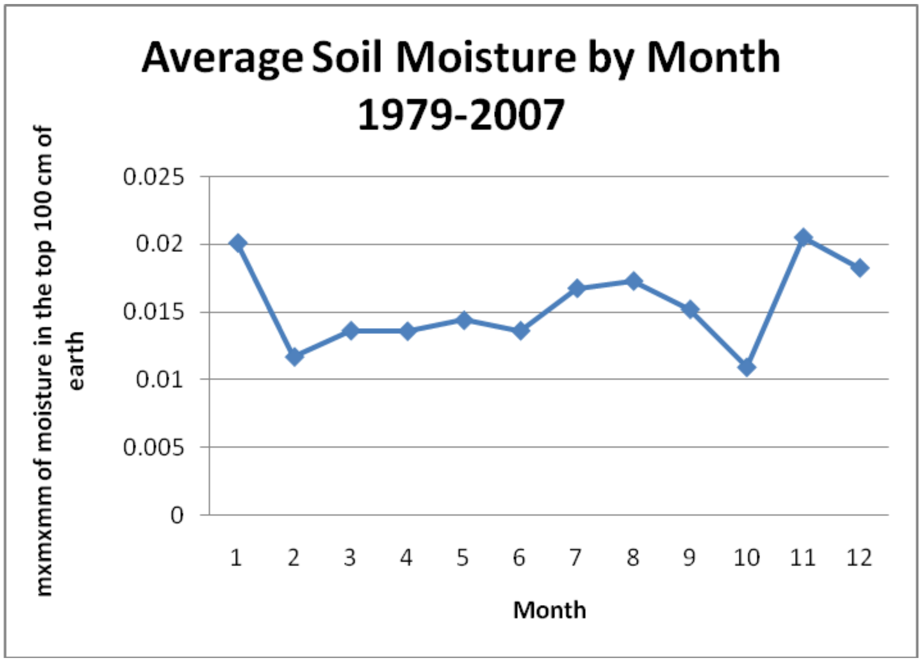
Month	Potential Evaporation Monthly Total	Evaporation Monthly total	Precipitation Monthly Total
1	86.62618	59.83951	77.86298
2	102.5576	51.96289	85.77361
3	155.8799	58.12042	88.20458
4	203.8854	55.93813	76.60705
5	241.9746	65.34079	121.8302
6	255.8272	72.15352	111.5201
7	294.6579	82.0411	67.12485
8	282.2831	101.5942	60.7364
9	219.4779	104.5554	73.54609
10	170.1182	105.5856	97.92048
11	111.6082	79.34025	88.88029
12	80.20371	65.11713	83.52337

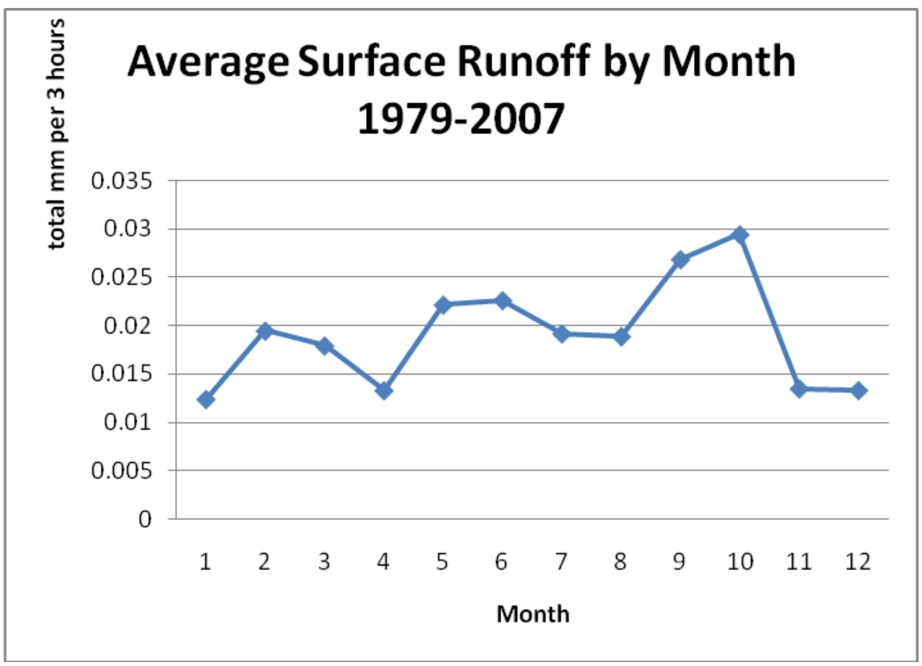

Average Temperature by Month
1979-2007
temperature in Kelvin
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
2
3
4
5
6
7
8
9
10
11
12
Month

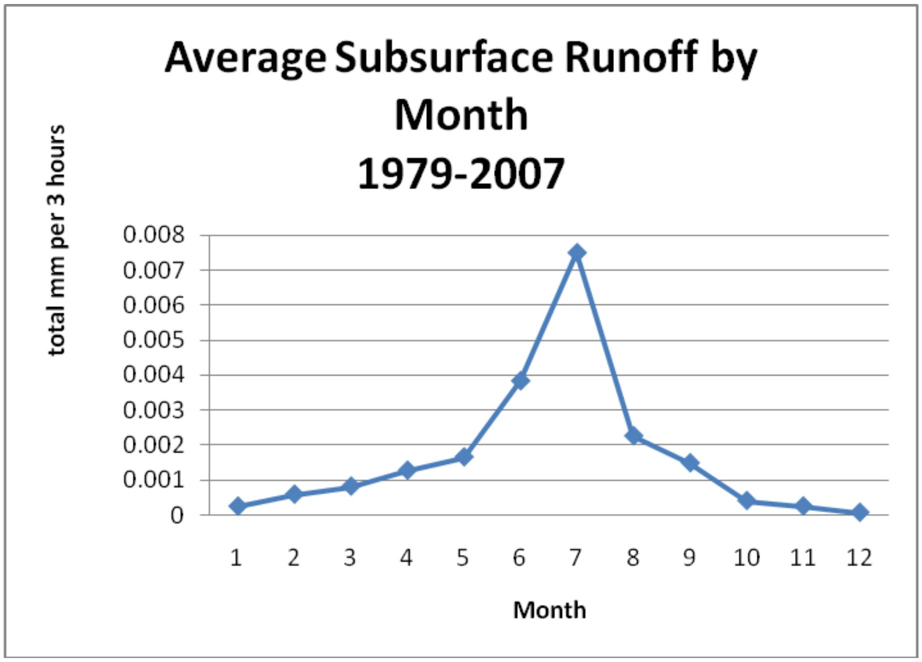

Average Precipitation by Month
1979-2007
total mm per 3 hours
0.0025
0.002
0.0015
0.001
0.0005
0
1
2
3
4
5
6
7
8
9
10
11
12
Month

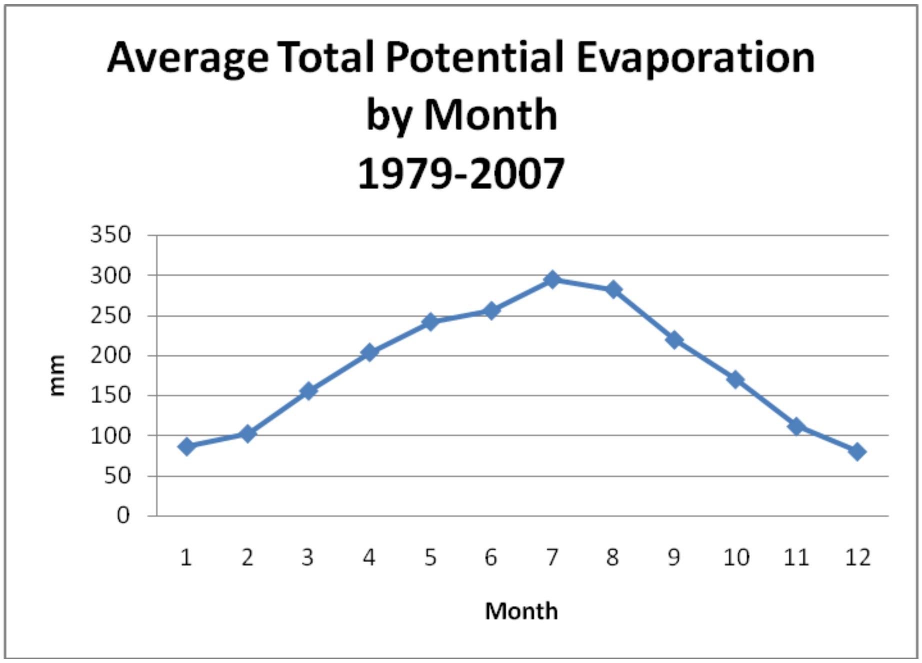

Average Potential Evaporation by Month
1979-2007
total mm per 3 hours
297
296
295
294
293
292
291
290
289
536.096442
424.0962424
438.0534123
455.7022893
486.3530897
472.7682792
526.6927634
499.2609191
504.0966573
417.6264735
498.2658369
509.2293464
Month

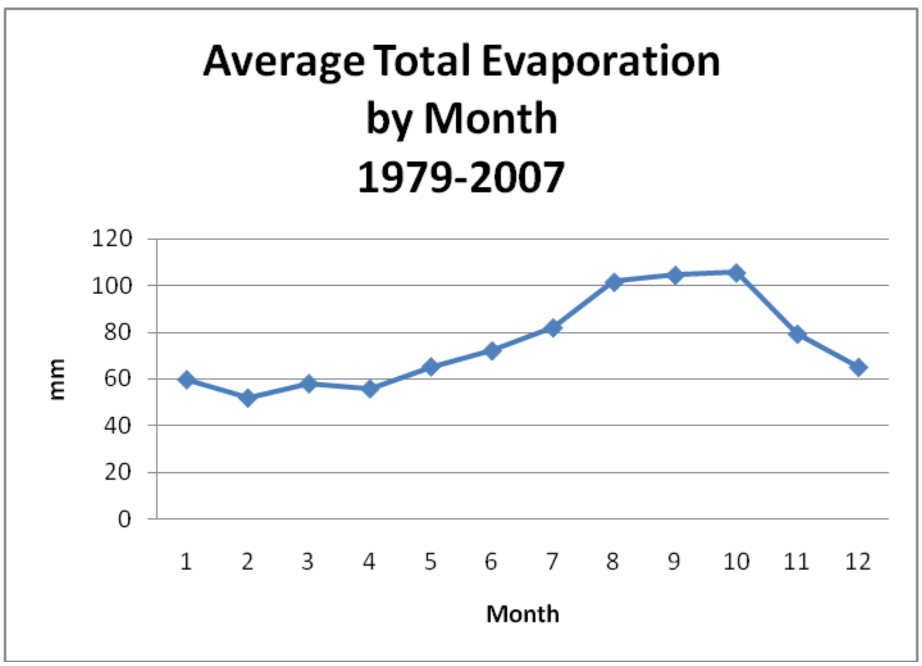

Average Evaporation by Month
1979-2007
total mm per 3 hours
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
2
3
4
5
6
7
8
9
10
11
12
Month

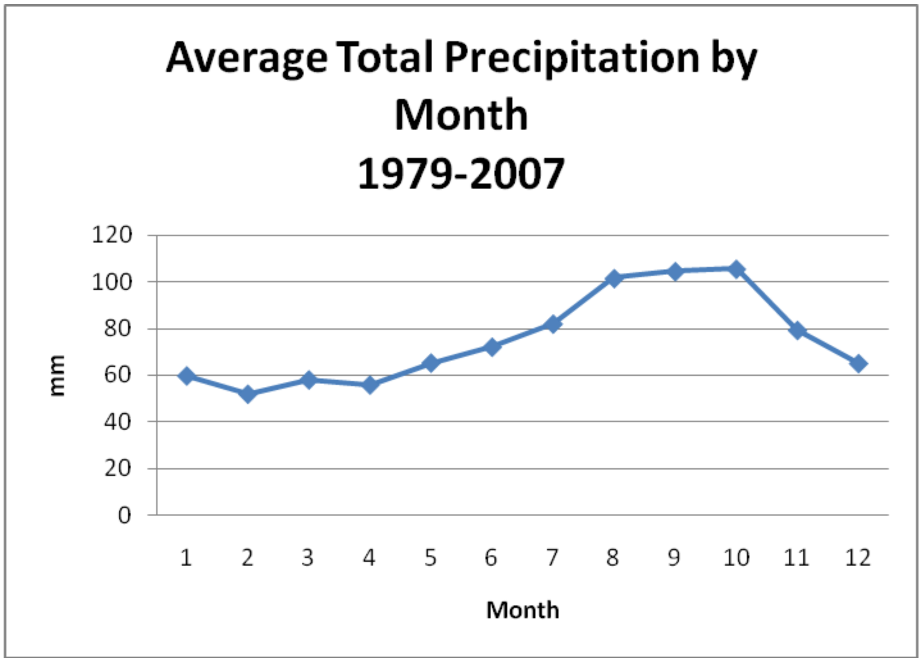

Average Soil Moisture by Month
1979-2007
mxmxmm of moisture in the top 100 cm of earth
0.025
0.02
0.015
0.01
0.005
0
1 2 3 4 5 6 7 8 9 10 11 12
Month


Average Surface Runoff by Month
1979-2007
total mm per 3 hours
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
1 2 3 4 5 6 7 8 9 10 11 12
Month


Average Subsurface Runoff by Month
1979-2007
total mm per 3 hours
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
1
2
3
4
5
6
7
8
9
10
11
12
Month

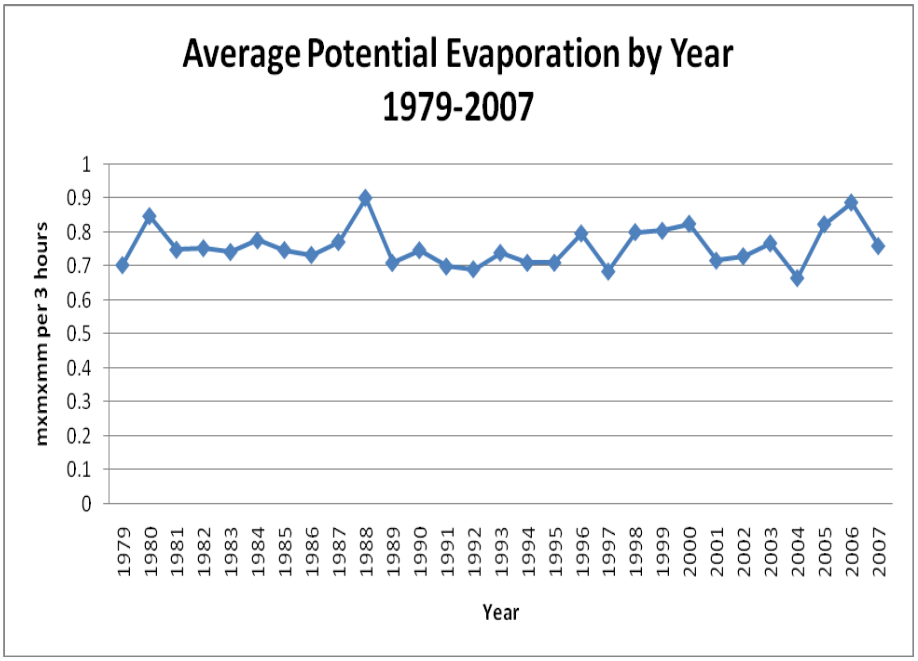

Average Total Potential Evaporation
by Month
1979-2007
350
300
250
200
150
100
50
0
mm
1
2
3
4
5
6
7
8
9
10
11
12
Month

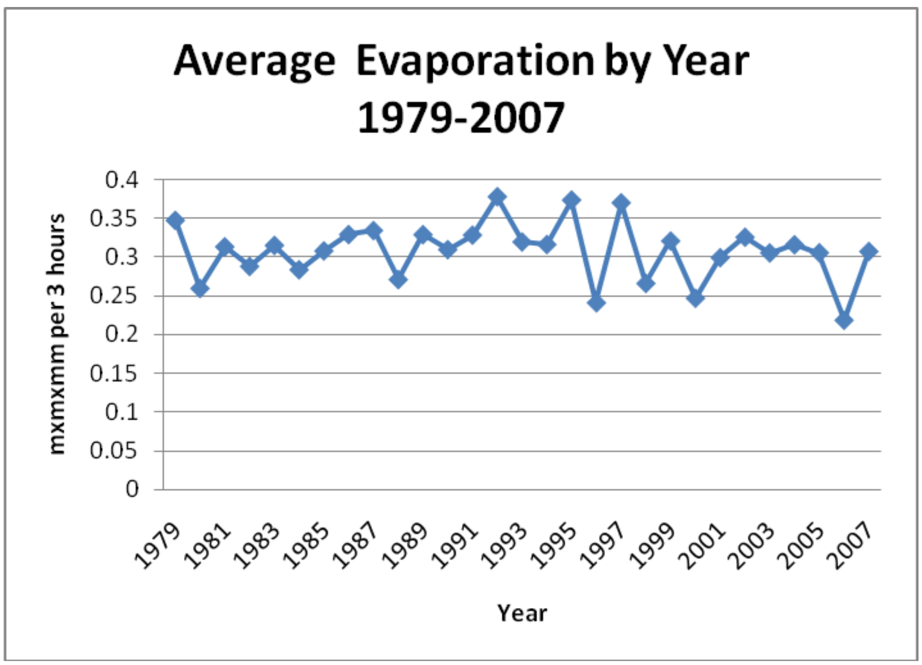

Average Total Evaporation
by Month
1979-2007
120
100
80
60
40
20
0
mm
1
2
3
4
5
6
7
8
9
10
11
12
Month

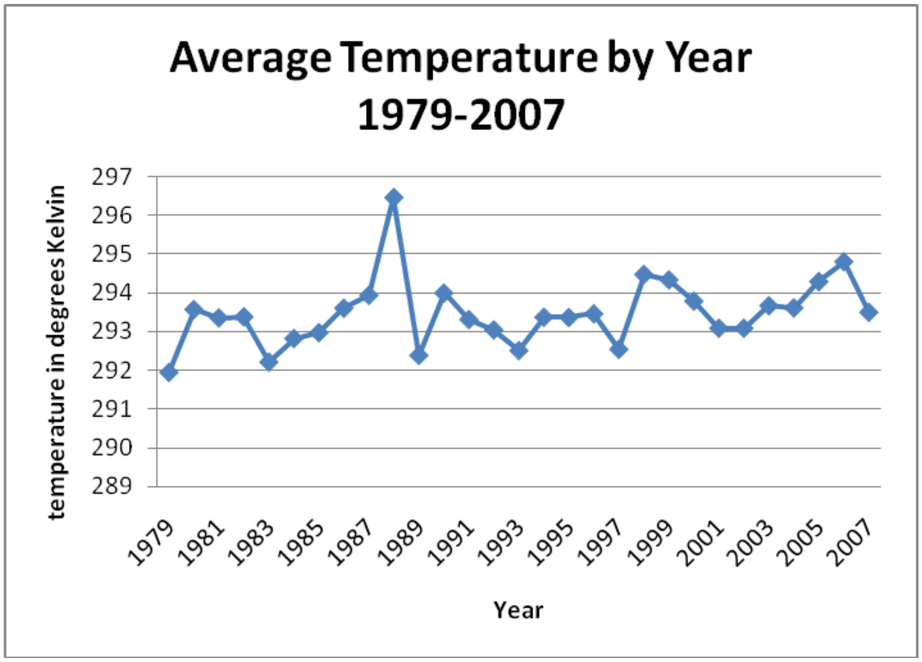

Average Total Precipitation by Month
1979-2007
120
100
80
60
40
20
0
mm
1
2
3
4
5
6
7
8
9
10
11
12
Month

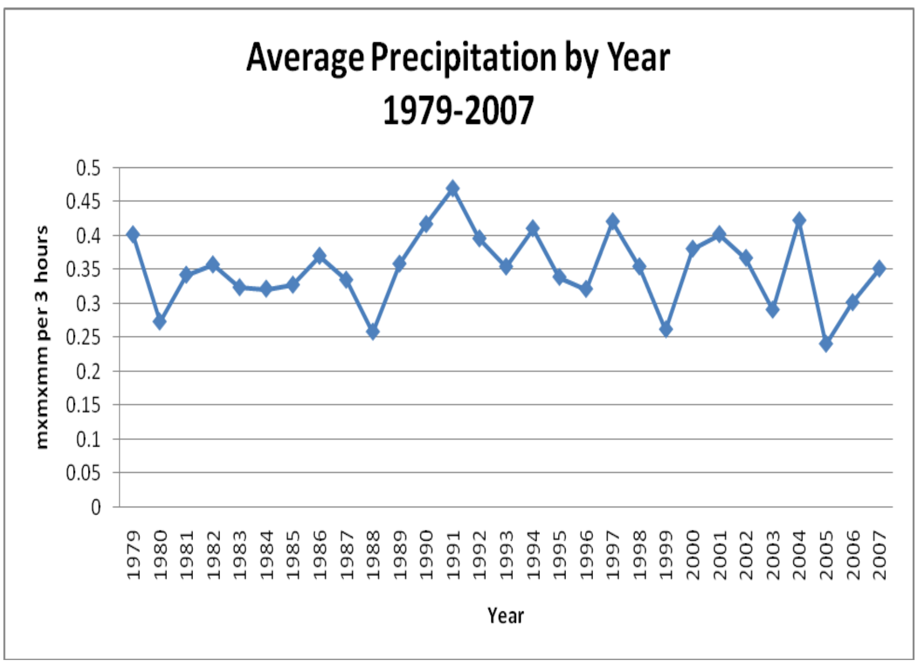
NARR by Year								
	Potential Evaporation (mm/3hrs)	Evaporation (mm/3hrs)	Precipitation (mm/3hrs)	Soil Moisture (mm in the top 100cm)	Subsurface Runoff (mm/3hrs)	Surface Runoff (mm/3hrs)	Temperature K	Temperature F
1979	0.70	0.347336824	0.40	536.10	0.002124453	0.020062365	291.95	67.64
1980	0.85	0.259884744	0.27	424.10	0.000565378	0.011701617	293.57	70.55
1981	0.75	0.313374996	0.34	438.05	0	0.013620478	293.35	70.16
1982	0.75	0.288320279	0.36	455.70	0	0.013586212	293.38	70.21
1983	0.74	0.315172755	0.32	486.35	0.000616776	0.014391452	292.22	68.12
1984	0.78	0.283902099	0.32	472.77	0.000633909	0.013620481	292.82	69.21
1985	0.75	0.308159542	0.33	526.69	0.000171327	0.016738624	292.97	69.48
1986	0.73	0.329142265	0.37	499.26	0.000119929	0.017269739	293.60	70.61
1987	0.77	0.334254617	0.33	504.10	0.001327004	0.015195128	293.93	71.21
1988	0.90	0.271305509	0.26	417.63	0.000776681	0.010942069	296.44	75.73
1989	0.71	0.328986774	0.36	498.27	0.000496849	0.020473555	292.39	68.43
1990	0.75	0.30972751	0.42	509.23	0.001576206	0.018229169	293.99	71.31
1991	0.70	0.328412032	0.47	555.63	0.004146113	0.023745898	293.31	70.09
1992	0.69	0.377762249	0.40	582.61	0.011958622	0.029331152	293.04	69.61
1993	0.74	0.319660216	0.35	552.32	0.000856634	0.02134732	292.51	68.65
1994	0.71	0.316410723	0.41	529.33	0.000239857	0.016224644	293.37	70.19
1995	0.71	0.373454555	0.34	568.64	0.003083883	0.027069635	293.36	70.18
1996	0.80	0.241523688	0.32	472.95	0	0.011119106	293.46	70.35
1997	0.69	0.369894577	0.42	574.61	0.003255212	0.029262622	292.55	68.71
1998	0.80	0.266330123	0.35	524.32	0.001524808	0.013654742	294.47	72.17
1999	0.80	0.320863069	0.26	500.68	0.000685307	0.020662014	294.33	71.92
2000	0.83	0.247328819	0.38	452.43	0	0.012712446	293.78	70.94
2001	0.72	0.29948453	0.40	560.57	0.008566342	0.020353625	293.09	69.69
2002	0.73	0.325738403	0.37	523.65	0.000753838	0.01632744	293.09	69.69
2003	0.77	0.305503456	0.29	516.89	0.003169548	0.01644737	293.67	70.73
2004	0.67	0.316075168	0.42	518.36	5.1398E-05	0.030907362	293.61	70.63
2005	0.82	0.305756487	0.24	493.28	0.001970259	0.024928052	294.28	71.84
2006	0.89	0.219034495	0.30	440.30	0	0.016995615	294.80	72.76
2007	0.76	0.307399639	0.35	505.15	0.001754056	0.018550499	293.50	70.42

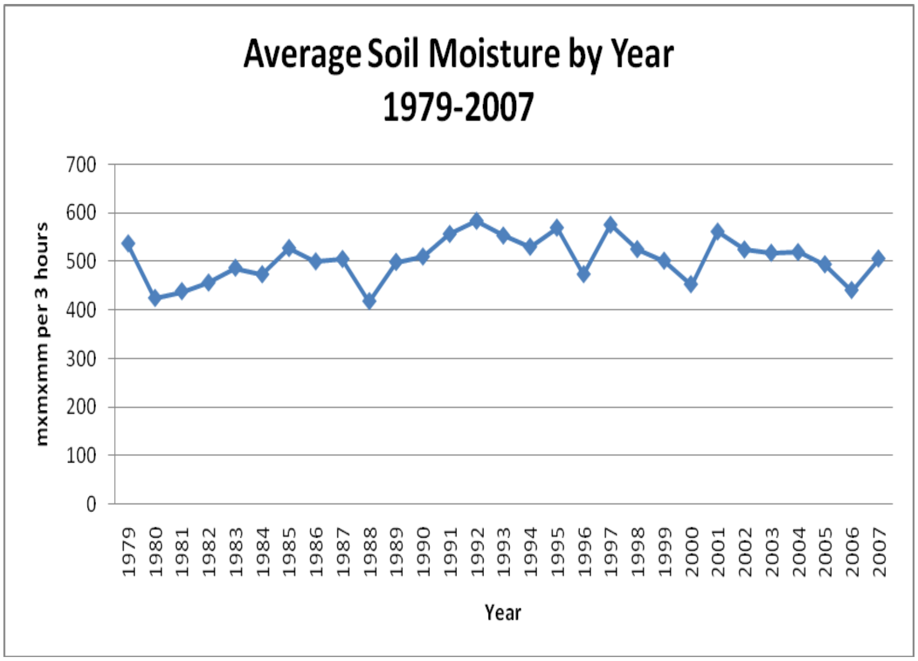
NARR Annual Values			
Year	Potential Evaporation Total Annual Values (mm)	Evaporation Total Annual Values (mm)	Precipitation Total Annual Values (mm)
1979	2058.024	1014.918	1174.335
1980	2477.759	759.3832	797.8771
1981	2188.982	915.6817	1000.149
1982	2202.918	842.4719	1044.643
1983	2169.887	920.9348	945.9108
1984	2269.437	829.5619	939.9948
1985	2186.584	900.4422	956.9046
1986	2144.782	961.7537	1081.971
1987	2255.507	976.692	978.6484
1988	2633.582	792.7547	754.5631
1989	2076.443	961.2994	1047.942
1990	2185.336	905.0238	1219.159
1991	2045.995	959.62	1373.228
1992	2022.06	1103.821	1157.23
1993	2163.269	934.0472	1035.536
1994	2077.44	924.5521	1200.774
1995	2077.494	1091.234	990.786
1996	2329.11	705.7322	939.0192
1997	2002.831	1080.832	1230.767
1998	2340.686	778.2166	1036.098
1999	2352.14	937.5619	764.8313
2000	2412.083	722.6948	1112.627
2001	2096.268	875.0938	1175.574
2002	2133.587	951.8076	1073.11
2003	2245.208	892.6811	849.155
2004	1946.15	923.5716	1235.382
2005	2407.74	893.4205	701.9404
2006	2594.39	640.0188	881.1687
2007	2221.129	898.2217	1027.005

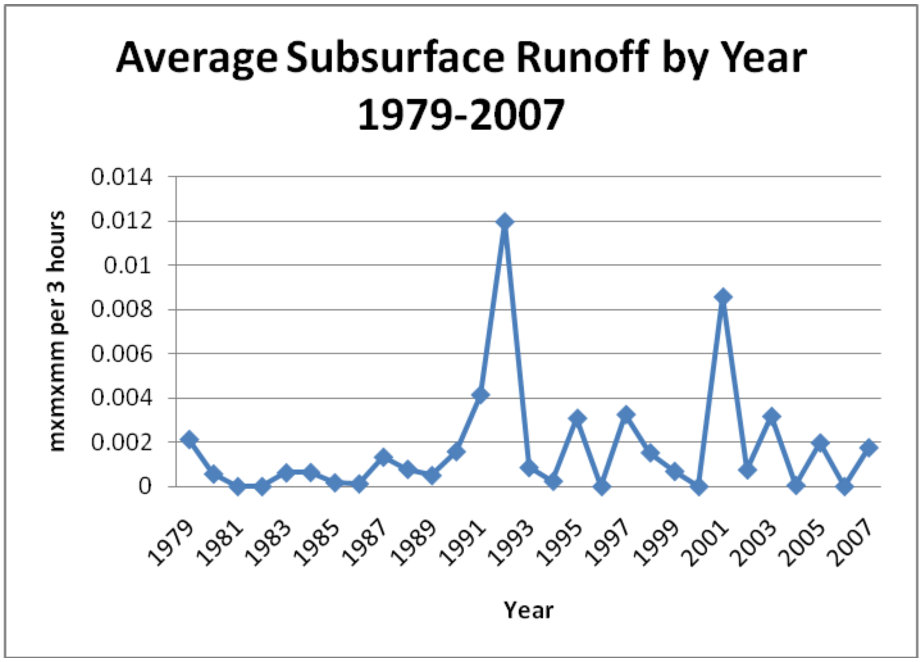

Average Potential Evaporation by Year
1979-2007
mxmxmm per 3 hours
Year

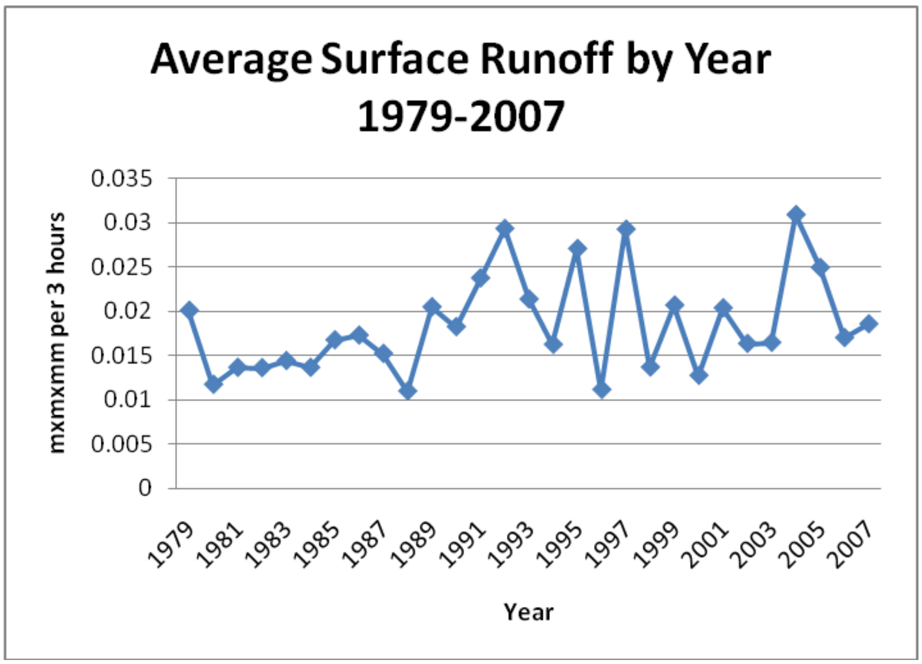

Average Evaporation by Year
1979-2007
mxmxmm per 3 hours
Year

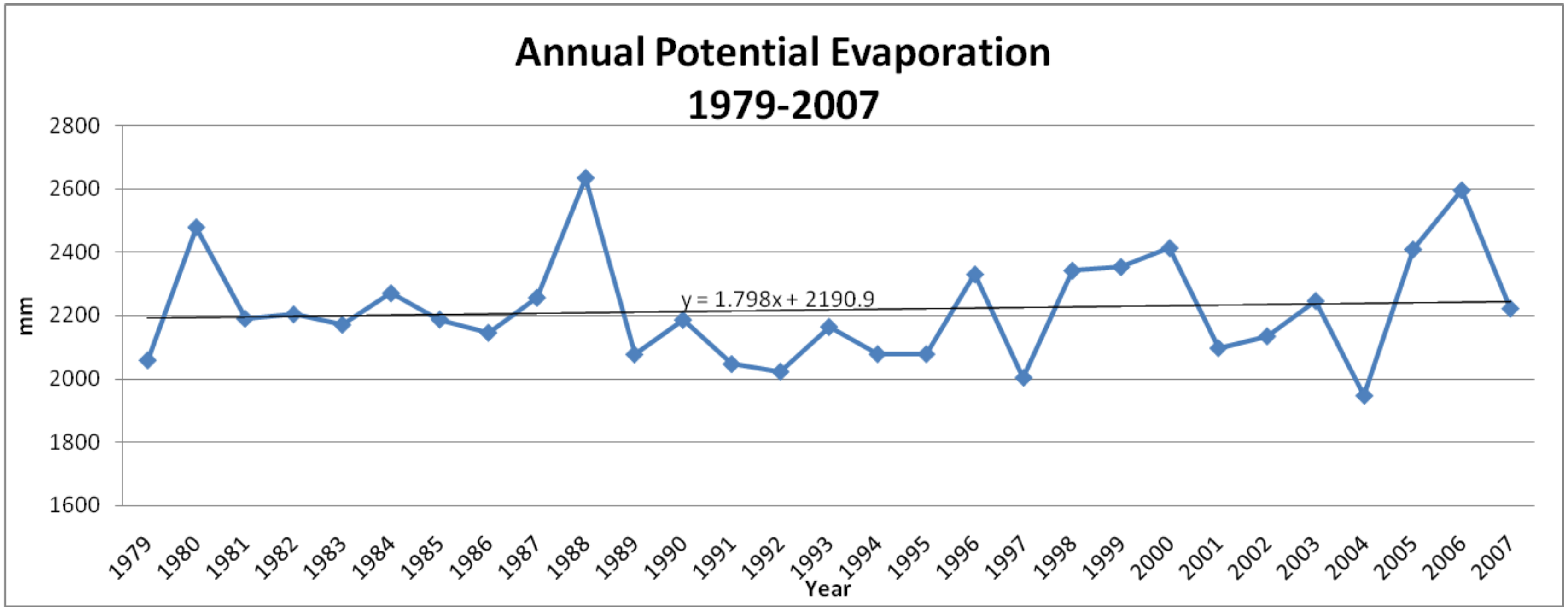

Average Temperature by Year
1979-2007
temperature in degrees Kelvin
297
296
295
294
293
292
291
290
289
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Year


Average Precipitation by Year
1979-2007
mxmxmm per 3 hours
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year

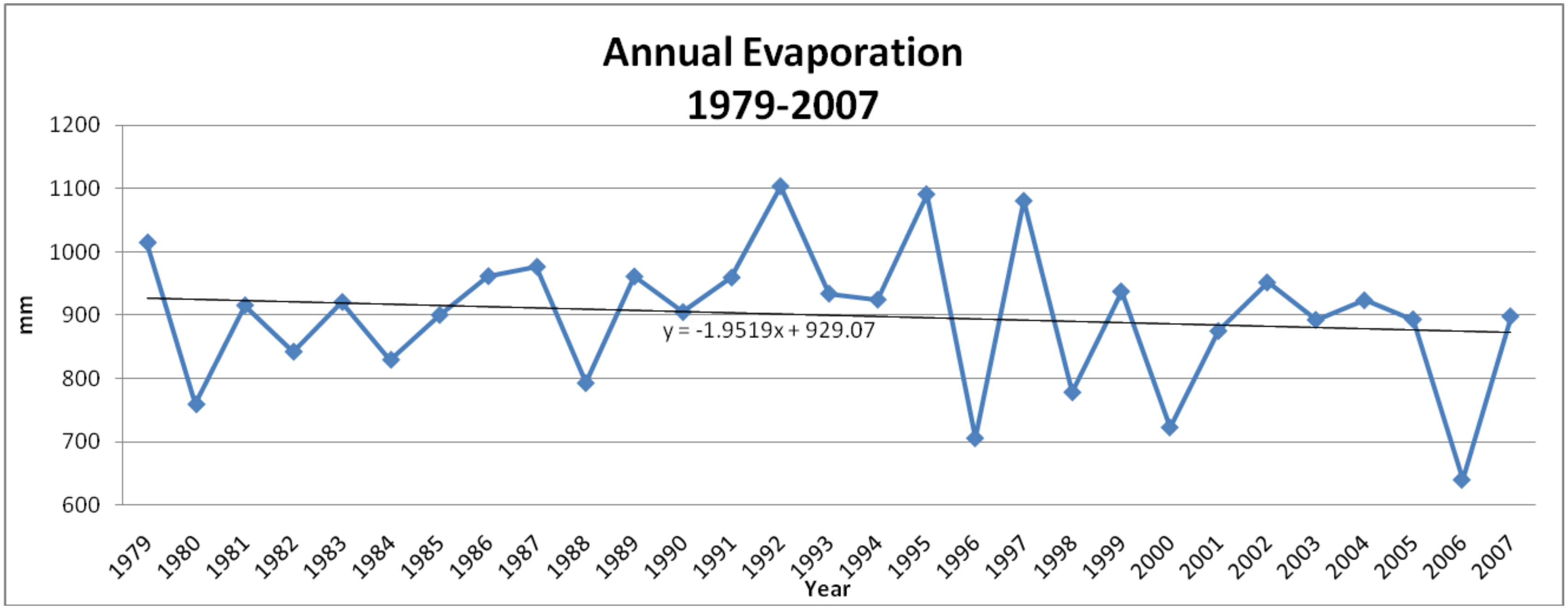

Average Soil Moisture by Year
1979-2007
mxmxmm per 3 hours
700
600
500
400
300
200
100
0
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year

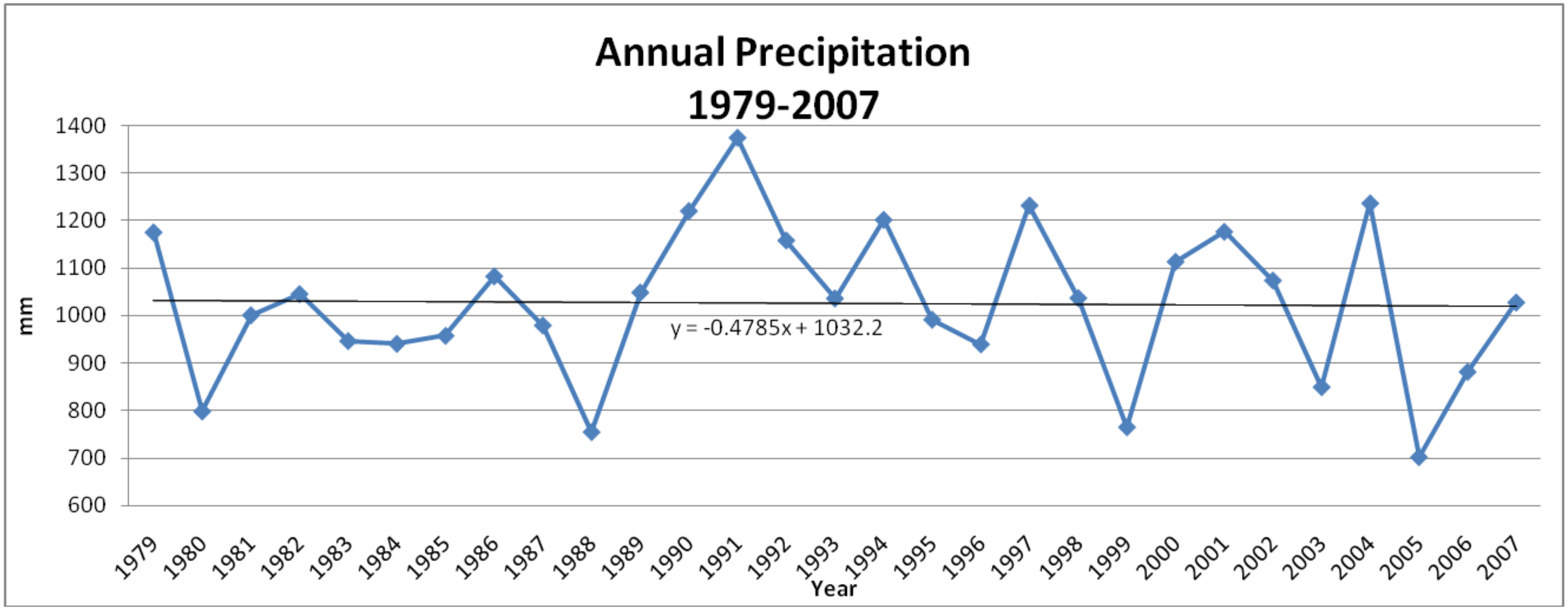

Average Subsurface Runoff by Year 1979-2007
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
mxmxmm per 3 hours
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Year

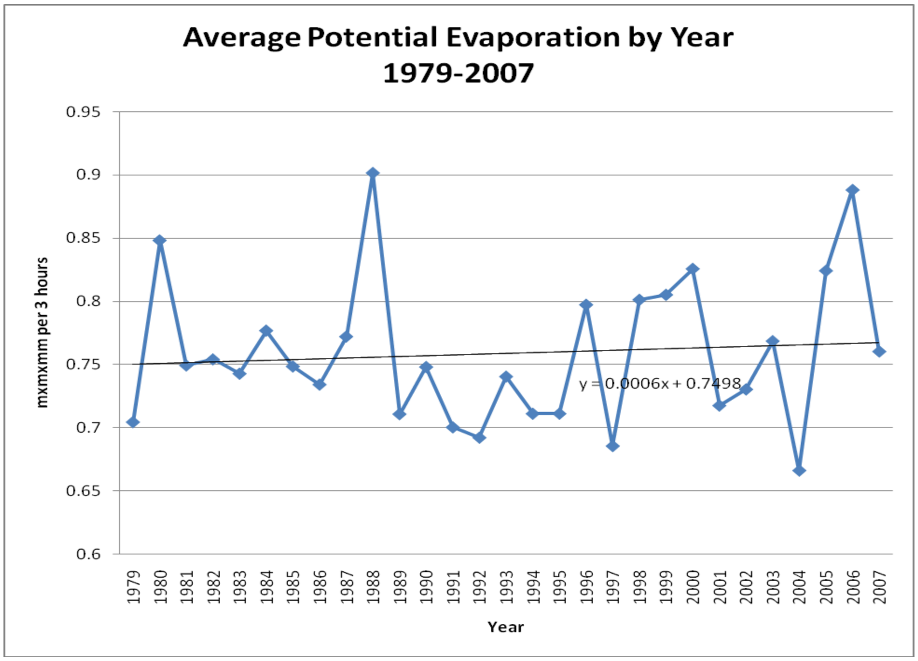

Average Surface Runoff by Year 1979-2007
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
mxmxmm per 3 hours
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Year



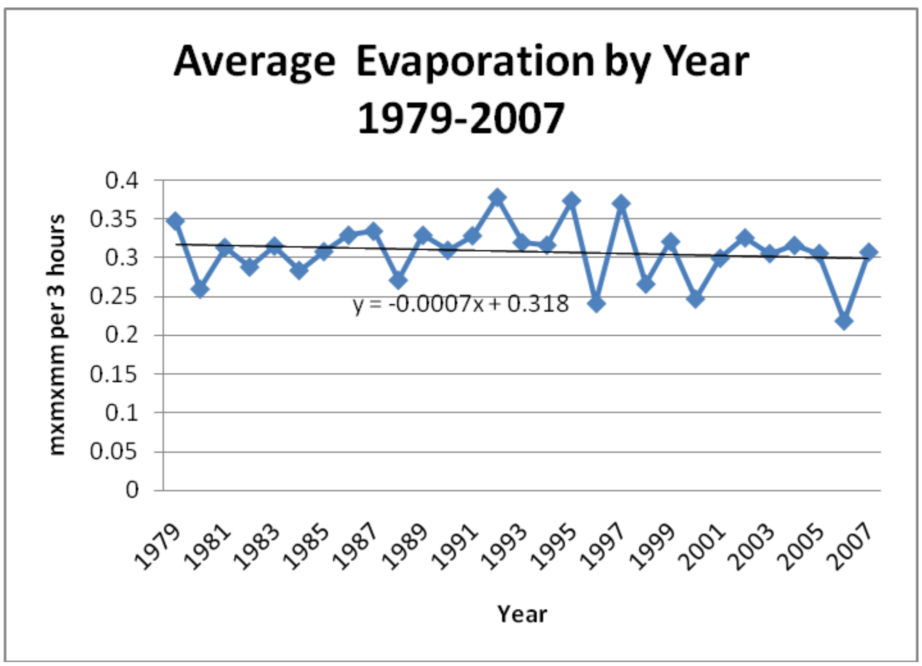
Annual Potential Evaporation
1979-2007
2800
2600
2400
2200
2000
1800
1600
mm
y = 1.798x + 2190.9
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year


Annual Evaporation
1979-2007
mm
Year
1200
1100
1000
900
800
700
600
y = -1.9519x + 929.07
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007

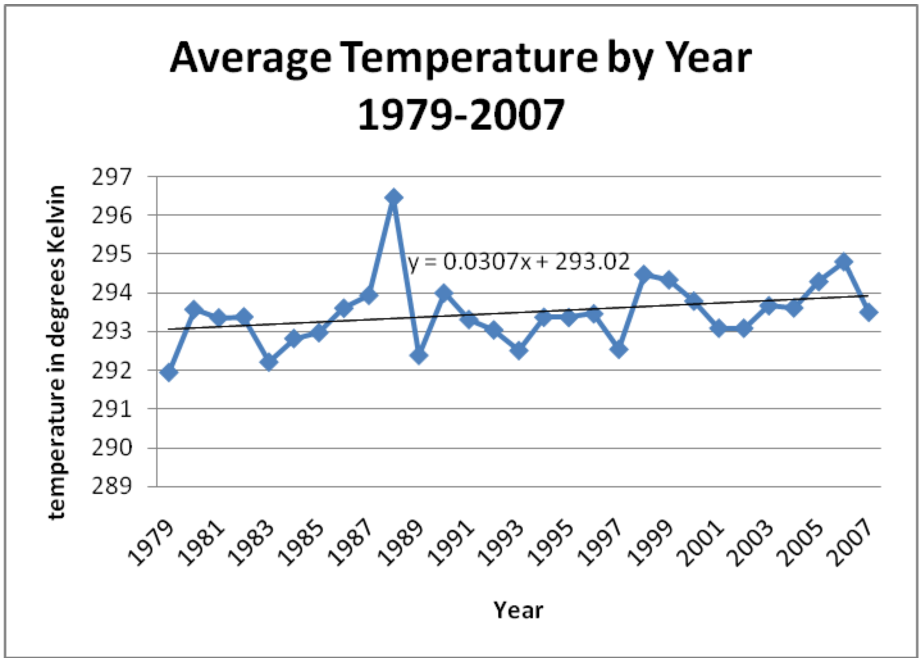

Annual Precipitation
1979-2007
mm
1400
1300
1200
1100
1000
900
800
700
600
y = -0.4785x + 1032.2
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year

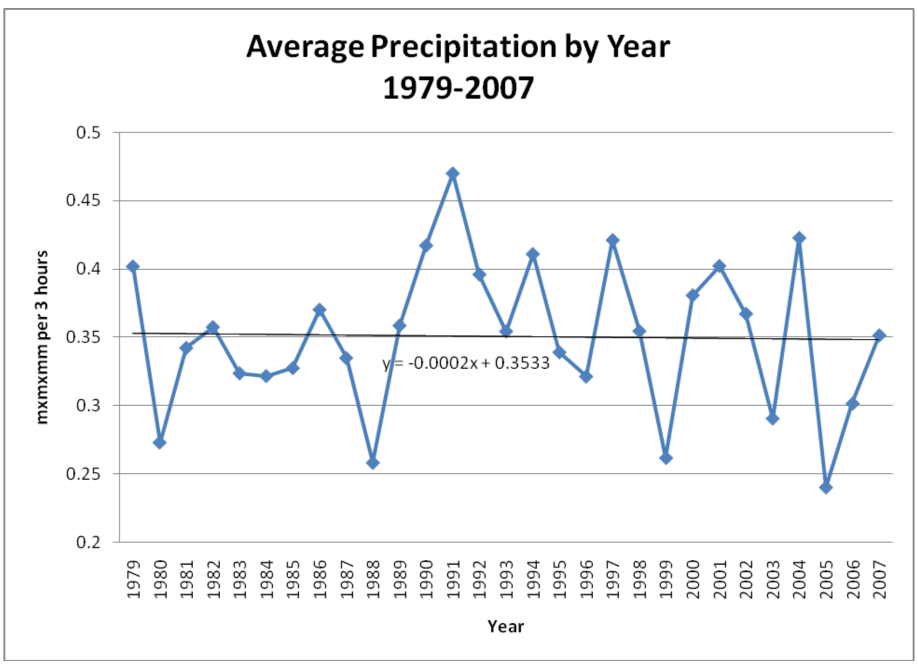


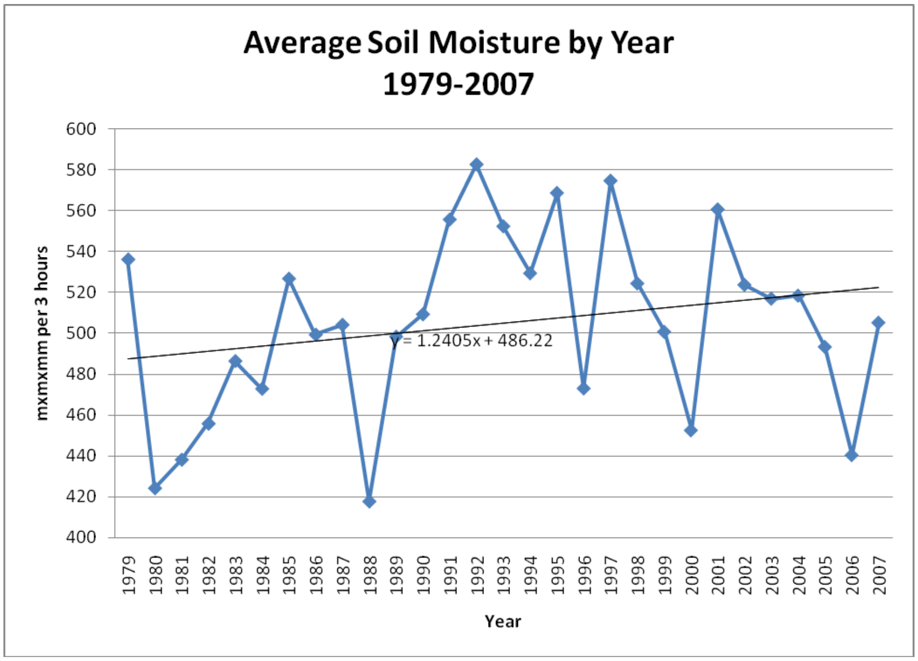
Average Potential Evaporation by Year
1979-2007
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
mxmxmm per 3 hours
y = 0.0006x + 0.7498
1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007
Year



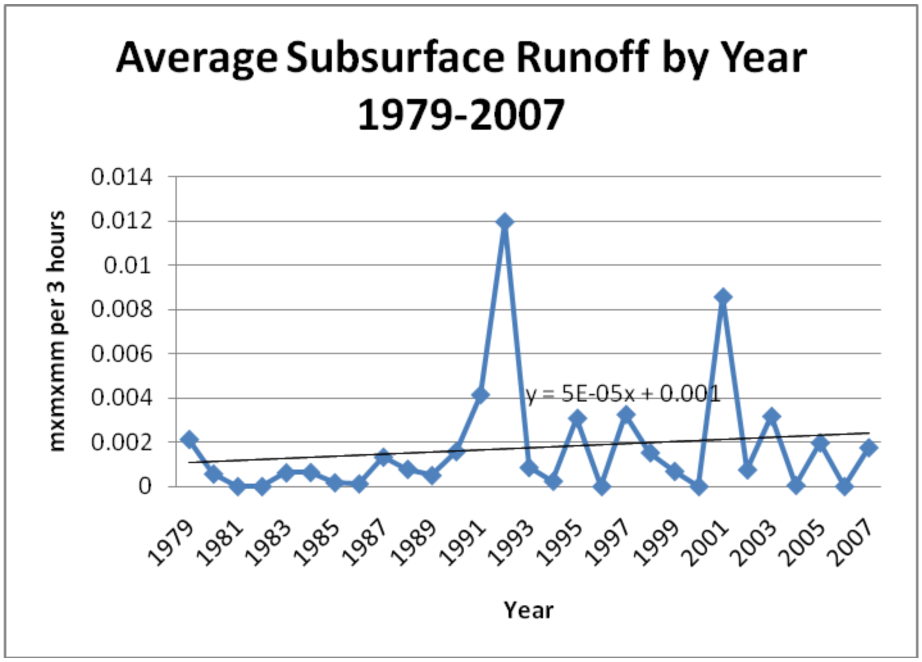
Average Evaporation by Year
1979-2007
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
mxmxmm per 3 hours
y = -0.0007x + 0.318
1979 1981 1983 1985 1987 1989 1991 1993 1995 1997 1999 2001 2003 2005 2007
Year

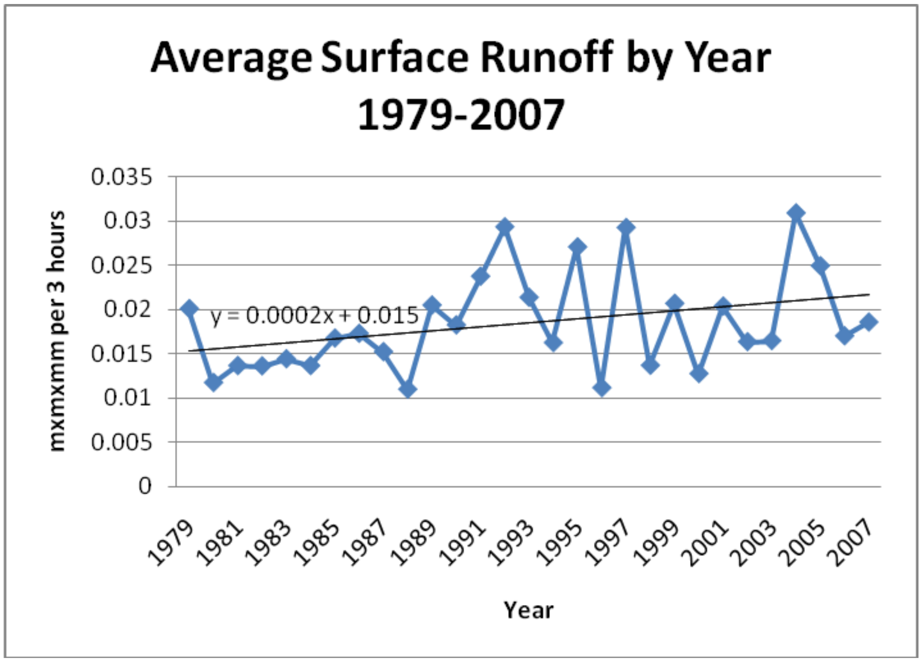

Average Temperature by Year
1979-2007
temperature in degrees Kelvin
297
296
295
294
293
292
291
290
289
y = 0.0307x + 293.02
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Year


Average Precipitation by Year
1979-2007
mxmxmm per 3 hours
0.5
0.45
0.4
0.35
0.3
0.25
0.2
y = -0.0002x + 0.3533
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year



Average Soil Moisture by Year
1979-2007
600
580
560
540
520
500
480
460
440
420
400
mxmxmm per 3 hours
y = 1.2405x + 486.22
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year


Average Subsurface Runoff by Year
1979-2007
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
mxmxmm per 3 hours
y = 5E-05x + 0.001
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Year


Average Surface Runoff by Year
1979-2007
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
mxmxmm per 3 hours
y = 0.0002x + 0.015
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Year

Appendix C

Python North American Regional Reanalysis:

Python code is used to create the time series data files for the North American Regional Reanalysis (NARR). The NARR provides climate data for North America from 1978 to the present. The climate variables used in the IDIS are temperature, potential evaporation, soil moisture and precipitation. These values are given as monthly averages. A monthly scheduled task retrieves the previous monthly data. NARR data is available in NetCDF format. The follow script converts the NetCDF files to a table format and averages the climate variables by location. The python code is explained in each step.

In the box below the basics of the program are established. The established code modules are loaded, the ArcGIS tools are loaded, and the program is told to overwrite the current files in the folder.

```
# ---------------------------------------------------------------------------
# NARR Conversion
# Created on: Fri Feb 24 2008
#   (generated by ArcGIS/ModelBuilder and Virginia Smith)
# ---------------------------------------------------------------------------

# Import system modules
import sys, string, os, arcgisscripting, glob, time

# Create the Geoprocessor object
gp = arcgisscripting.create()

#Set the input workspace
```

```
root = 'O:\\GISDATA\\codes\\NARR\\NetCDF\\' # one specific folder
outputFolder = 'O:\\GISDATA\\codes\\NARR\\Outputs\\'

#Load required toolboxes...
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Multidimension Tools.tbx")
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management Tools.tbx")
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx")

gp.overwriteoutput=1
```

In this modules the NetCDF files downloaded from NARR are looped through. This module of code also renames each NetCDF file to be named by the year and month that it represents.

```
for folder in glob.glob(root):
    layer_file_list = ""
    #Loop through the list of netcdf files
    for file in glob.glob(root + 'narrmon-a_221_*.nc'):
        folder, file_name = os.path.split(file)
        file_name = file_name.split("\\")[-1].split("_")[2]

        # Local variables...
        file_name = file_name+".lyr"
```

The module of code below converts each NetCDF file to a feature layer. The feature layer created is a grid of point data representing the four climate variables used. A feature is created for every month of every year from 1978 to the previous month.

```
	# Process: Make NetCDF Feature Layer...
	gp.MakeNetCDFFeatureLayer_md(file,
"Potential_evaporation;Soil_moisture_content;Temperature;Total_precipitation;time",
"x", "y", outputFolder + "\\" + file_name, "y;x", "", "", "", "BY_VALUE")

	# Process: Save To Layer File...
	gp.SaveToLayerFile_management(outputFolder + "\\" + file_name, outputFolder +
"\\" + file_name)
```

The module of code below links each new feature layer with the layer counties from the dynamic geodatabase. The new feature layers are linked to the counties layer through a spatial join. The nature of this spatial join aggregates the NARR grid points contained within each county.

```
# Local variables...
Narr_counties_shp = outputFolder + "\\" + file_name.replace("-
","_").replace(".","_")+".shp" # Remove hyphens and periods from the file name.  These
are invalid characters for the upcoming spatial join function when creating our output
shapefile.
NARR = outputFolder + "\\" + file_name
Counties =
"O:\\GISDATA\\mxds\\SpatialTimeData\\SpatialTimeDataLayers.gdb\\counties"

# Process: Spatial Join...
gp.SpatialJoin_analysis(Counties, NARR, Narr_counties_shp,
"JOIN_ONE_TO_ONE", "KEEP_ALL", "NAME NAME true true false 50 Text 0 0
,First,#,O:\\GISDATA\\mxds\\SpatialTimeData\\SpatialTimeDataLayers.gdb\\counties,N
AME,-1,-1;climate_re climate_region true true false 2 Short 0 0
,First,#,O:\\GISDATA\\mxds\\SpatialTimeData\\SpatialTimeDataLayers.gdb\\counties,n,
-1,-1;FeatureID FeatureID true true false 4 Long 0 0
,First,#,O:\\GISDATA\\mxds\\SpatialTimeData\\SpatialTimeDataLayers.gdb\\counties,F
eatureID,-1,-1;", "INTERSECTS", "0 Unknown")
```

As the spatial join files are created they are add to a file list. Then, the files from the layer list are merged into one feature file.

```
    layer_file_list = layer_file_list + "'" + Narr_counties_shp + "';"

    # Local variables...
    Output_Dataset =
"O:\\GISDATA\\mxds\\SpatialTimeData\\SpatialTimeDataLayers.gdb\\NARR_counties"
    layer_file_list = layer_file_list.rstrip(";")
    Input_Datasets = layer_file_list

    # Process: Merge...
    gp.Merge_management(Input_Datasets, Output_Dataset, layer_file_list)
```

The files are then tailored to a format compatible for supporting time series. The climate variable fields are renamed by their VarID, and unnecessary fields are deleted.

```
# Local variables...
  NARR_counties =
"O:\\GISDATA\\mxds\\SpatialTimeData\\SpatialTimeDataLayers.gdb\\NARR_counties"

    # Process: Add Field...
    gp.AddField_management(NARR_counties, "FeatureID", "LONG", "", "", "",
"FeatureID", "NULLABLE", "NON_REQUIRED", "")

    # Process: Calculate Field...
    gp.CalculateField_management(NARR_counties, "FeatureID", "[HydroID]", "VB", "")

    # Process: Add Field (2)...
    gp.AddField_management(NARR_counties, "VID30", "DOUBLE", "", "", "",
"VID30", "NULLABLE", "NON_REQUIRED", "")
```

```
    # Process: Calculate Field (2)...
    gp.CalculateField_management(NARR_counties, "VID30", "[Potential_]", "VB", "")

    # Process: Add Field (3)...
    gp.AddField_management(NARR_counties, "VID50", "DOUBLE", "", "", "",
"VID50", "NULLABLE", "NON_REQUIRED", "")

    # Process: Calculate Field (3)...
    gp.CalculateField_management(NARR_counties, "VID50", "[Soil_moist]", "VB", "")

    # Process: Add Field (4)...
    gp.AddField_management(NARR_counties, "VID60", "DOUBLE", "", "", "",
"VID60", "NULLABLE", "NON_REQUIRED", "")

    # Process: Calculate Field (4)...
    gp.CalculateField_management(NARR_counties, "VID60", "[Temperatur]", "VB", "")

    # Process: Delete Field (2)...
    gp.DeleteField_management(NARR_counties,
"Join_Count;OBJECTID_1;NAME;climate_re;Shape_Leng;Shape_Area;HydroID;Potent
ial_;Soil_moist;Temperatur")
```

Appendix D

Python Code for Creating Depth Rasters Daily

```
# ---------------------------------------------------------------------------
# Depth.py
# Created on: Mon Feb 04 2008 10:55:11 AM
#   (generated by ArcGIS/ModelBuilder and Virginia Smith)
# ---------------------------------------------------------------------------

# Import system modules
import sys, string, os, arcgisscripting, csv

# Create the Geoprocessor object
gp = arcgisscripting.create()

# Check out any necessary licenses
gp.CheckOutExtension("3D")

# Load required toolboxes...
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/3D Analyst
Tools.tbx")

gp.overwriteoutput = 1
```

```
import glob
for file in glob.glob("O:\\GISData\\bathy\\trial\\b*.aux"):
   folder, file_name = os.path.split(file)
   file_name = file_name.strip('b')
   file_name=file_name.strip('.aux')
   reader=csv.reader(open("reservoir_eleveation.csv","rb"))
   for row in csv.reader (['id_num,name, id_name, elev']):
      for id_num, name, id_name, elev in reader:
```

```
         if id_num == file_name:
            # Local variables...
            Output_raster = ‘O:\\GISData\bathy\\trial\\output\\depth'+file_name
            Input_raster = ‘O:\\GISData\\bathy\\trial\\b'+file_name
            Constant_value_2 = elev

            # Process: Minus...
            gp.Minus_3d(Input_raster, Constant_value_2, Output_raster)
```

Appendix E

Drought Education

Table of Contents

What is Drought?

> *"We have no good definition of drought. We may say truthfully that we scarcely know a drought when we see one. We welcome the first clear day after a rainy spell. Rainless days continue for a time and we are pleased to have a long spell of such fine weather. It keeps on and we are a little worried. A few days more and we are really in trouble. The first rainless day in a spell of fine weather contributes as much to the drought as the last, but no one knows how serious it will be until the last dry day is gone and the rains have come again... we are not sure about it until the crops have withered and died."*
> Drought and Its Causes and Effects, *Tannehill (1947)* [1]

The word "drought" can imply several things. However, the most basic definition of drought is a deficiency in precipitation for an extended period of time. [2] It's difficult to establish when a drought is truly on setting. When do a string of sunny days turn into a drought? The question can be answered differently according to the type of drought that is being analyzed (see the Types of Drought Link below). [3] The range of definitions for droughts can be defined by rainfall amounts, vegetation conditions, agricultural productivity, soil moisture, levels in reservoirs, stream flow or economic impacts. It results in water shortages for residents, farmers, industry, and environments. [1] Drought is a natural reoccurring hazard of nature, which varies by region. There isn't a standard number of sunny days that define drought; drought must be defined relative to "normal" water balance for that region.[3]

Types of drought

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Why Do Droughts Occur?

There is still much debate over why droughts occur. Droughts are reoccurring events that are largely the result of fluctuations in climate. They are caused by a decrease in the amount of water in a water balance for a given region. There are so many variables that are believed to contribute to the onset of drought that science has yet to isolate the exact causes of drought. However, science has been able to identify several factors that induce drought. Some of the factors scientists study are listed below (from the National Drought Mitigation Center). [3]

Global Weather Patterns
A great deal of research has been conducted in recent years on the role of interacting systems, or teleconnections, in explaining regional and even global patterns of climatic variability. These patterns tend to recur periodically with enough frequency and with similar characteristics over a sufficient length of time that they offer opportunities to improve our ability for long-range climate prediction, particularly in the tropics. One such teleconnection is the El Niño/Southern Oscillation (ENSO). [3]

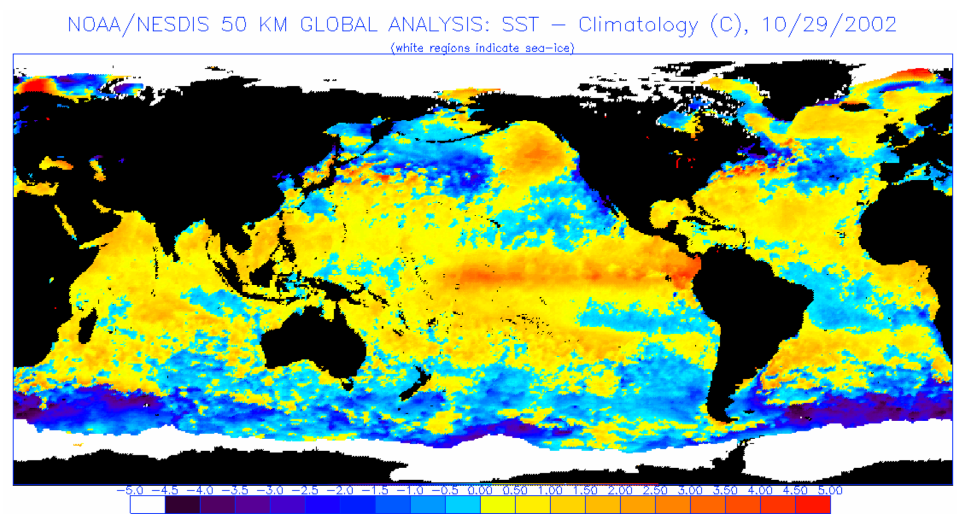

Figure 1: A satellite image produced by NOAA to show the impacts of El Nino on 2002 on global weather systems. [4]

High Pressure
The immediate cause of drought is the predominant sinking motion of air (subsidence) that results in compressional warming or high pressure, which inhibits cloud formation and results in lower relative humidity and less

precipitation. Regions under the influence of semipermanent high pressure during all or a major portion of the year are usually deserts, such as the Sahara and Kalahari deserts of Africa and the Gobi Desert of Asia. Most climatic regions experience varying degrees of dominance by high pressure, often depending on the season. Prolonged droughts occur when large-scale anomalies in atmospheric circulation patterns persist for months or seasons (or longer). The extreme drought that affected the United States and Canada during 1988 resulted from the persistence of a large-scale atmospheric circulation anomaly. [3]

Too Many Variables

Scientists don't know how to predict drought a month or more in advance for most locations. Predicting drought depends on the ability to forecast two fundamental meteorological surface parameters, precipitation and temperature. From the historical record we know that climate is inherently variable. We also know that anomalies of precipitation and temperature may last from several months to several decades. How long they last depends on air–sea interactions, soil moisture and land surface processes, topography, internal dynamics, and the accumulated influence of dynamically unstable synoptic weather systems at the global scale. [3]

The potential for improved drought predictions in the near future differs by region, season, and climatic regime.

The Tropical Outlook

In the tropics, for example, meteorologists have made significant advances in understanding the climate system. Specifically, it is now known that a major portion of the atmospheric variability that occurs on time scales of months to several years is associated with variations in tropical sea surface temperatures. The Tropical Ocean Global Atmosphere (TOGA) project has produced results that suggest that it may now be possible to predict certain climatic conditions associated with ENSO events more than a year in advance. For those regions whose climate is greatly influenced by ENSO events, TOGA project results may help produce more reliable meteorological forecasts that can reduce risks in those economic sectors most sensitive to climate variability and, particularly, extreme events such as drought. [3]

The Temperate Zone Outlook

In the extratropical regions, current long-range forecasts are of very limited reliability. The ability that does exist is primarily the result of empirical and statistical relationships. In the tropics, empirical relationships have been demonstrated to exist between precipitation and ENSO events, but few such relationships have been confirmed above 30 north latitude. Meteorologists do not believe that reliable forecasts are attainable for all regions a season or more in advance. [3]

Additional Information About the Water Balance and the Water Cycle

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How are Droughts Predicted?

At this time droughts can not be fully predicted. In fact, it is difficult to tell when a drought is beginning (or if it is a spell of sunny weather). In some regions drought can be defined by few days without rain (rain forest areas); while, other locations can go months without rain and still not be in true drought (dessert areas). [1] It is also difficult to know when a drought is ending. Some droughts (like the 1950s drought of Texas) are broken up by a wet spell. [5] Wet spells sometimes occur during droughts, but do not last long enough for the area to recover from drought. Although scientists cannot fully predict droughts, they have identified several variables that affect drought to get an idea of when and where droughts will occur. [6] The variables that are studied to predict drought are global weather patterns, high pressure, the tropical outlook, and the temperate zone outlook (see the previous section, “Why do Droughts Occur?”). [3]

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What Are the Impacts of Drought?

The impacts of drought can be divided in to three main groups: economic, social and environmental. Some examples of these types of impacts are listed below in Table 1. [3]

Type of Impact	Examples of Impacts
Economic	Costs and losses to agricultural and livestock producers, loss of fishery productions, decrease in land prices, loss in industries/manufacturers, unemployment, strain on financial institutions (foreclosures, credit risk and capital shortfalls), government revenue loss, decrease in recreational businesses and tourism, increase in energy demand, reduction in energy supply, cost of water transport/transfer and supplemental water resources, increase in food prices, and increase in food importation
Social	Rural population loss, health, increased conflicts, reduced quality of life, public dissatisfaction with government drought response increased data/information needs, coordination of dissemination activities, recognition of institutional restraints on water use
Environmental	Damage to animal species and plant communities, increase in the number of wild fires, wind/water erosion of soils, poor air quality, decrease in visual and landscape quality, lower water body levels, reduced flow from springs, reduced stream flow, loss of wetlands, salinity fluctuations in bays and estuaries, groundwater depletion, and negative effects on water quality.

Table 1: Types of drought impacts and their implications. [3]

Certain regions are more susceptible to drought impacts. This can be analyzed using a drought vulnerability tree diagram. Tree diagrams analyze drought vulnerability by significant drought impacts for a region. These show how susceptible a region is to specific drought risks. Two examples of a tree diagram are shown below. Figure 2 shows a tree diagram of agricultural impact analysis. Figure 3 is an example of tree diagram for urban drought impact analysis. [3]

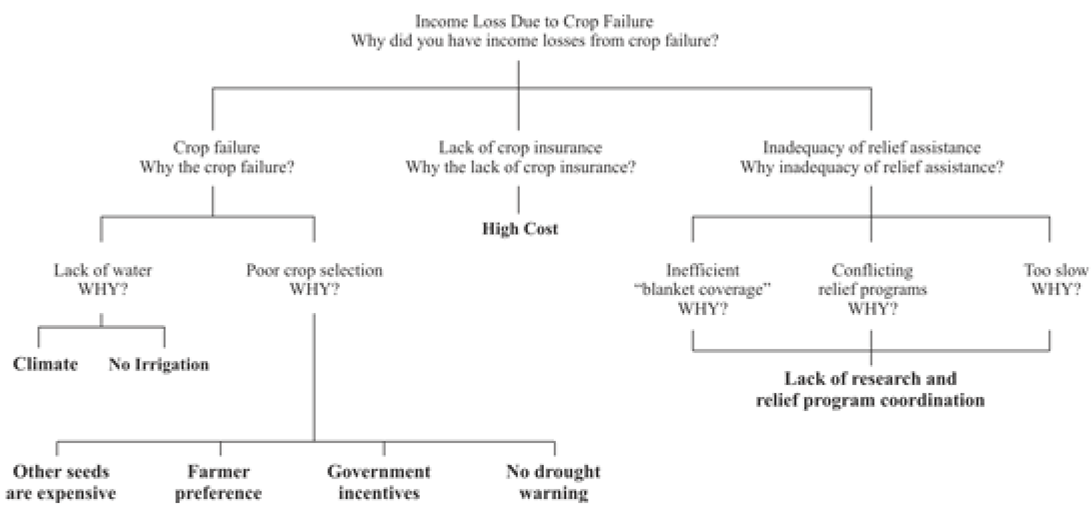

Figure 2: An example of a simplified agricultural impact tree diagram. (Notice the boldface represents the basal causes of the listed impact. Although these items may be broken down further, this example illustrates the vulnerability assessment process.) (From the National Drought Mitigation Center) [3]

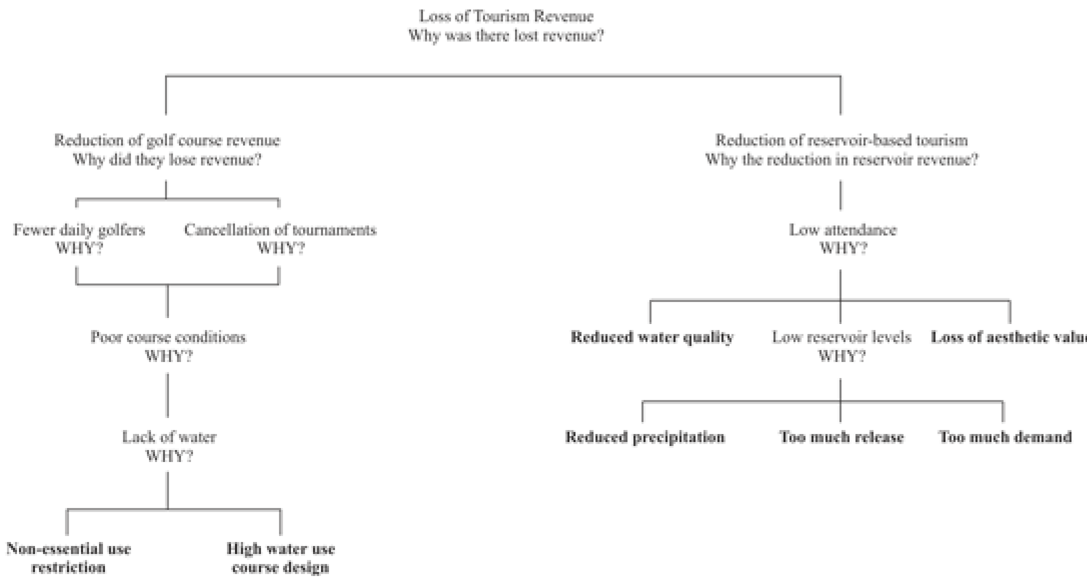

Figure 3: An example of a simplified urban impact tree diagram. (Notice the boldface items represent the basal causes of the listed impact [in this case, the loss of tourism revenue]. Although these items may be broken down further, this example illustrates the vulnerability assessment process.) (From the National Drought Mitigation Center) [3]

[Assistance to Drought-Impacted Areas]

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How is Drought Severity Defined?

Drought severity is measured according to the type of drought that is being analyzed. All measurements of drought are based on indices of drought severity. Drought indices take several variables into account; such as, precipitation, soil moisture, snow pack, and other water supply indicators. Indices differ by the variable implemented and the weight that is given to each variable. Some examples of popular indices are: the Standardized Precipitation Index, Palmer Drought Severity Index, Crop Moisture Index, Surface Water Supply Index, and Reclamation Drought Index. Also, drought severity can be studied by analyzing climate and water availability (reservoir capacity, soil moisture, or stream flow) percent of normal. More can be read about these types of rating systems at the National Drought Mitigation Center website (see the link below in the "Links" section of the report). [3]

For the Republic of Texas, the method of measuring drought severity is decided by climate region. Each region decides the point at which drought regulations should come into effect. [7] The Trinity River Basin is located mainly in Water Management Region C and H (with small areas also belonging to Regions D, G, I). The river basin is mainly located in the Northeast region of the Climate Regions for Texas. A map of these regions can be seen in figure 4. [8] However, in the case of the Trinity River Basin the Climate Regions have agreed to give water available jurisdiction to the Trinity River Authority (TRA). The TRA has established general drought contingency triggers on the State Drought Preparedness Plan. However, for the Basin the functional drought contingency triggers are established on the water users group. Each water users group has its own triggers and set of responses. A list of drought contingency triggers and responses can be found in the Trinity River Basin Master Plan – 2001. [9]

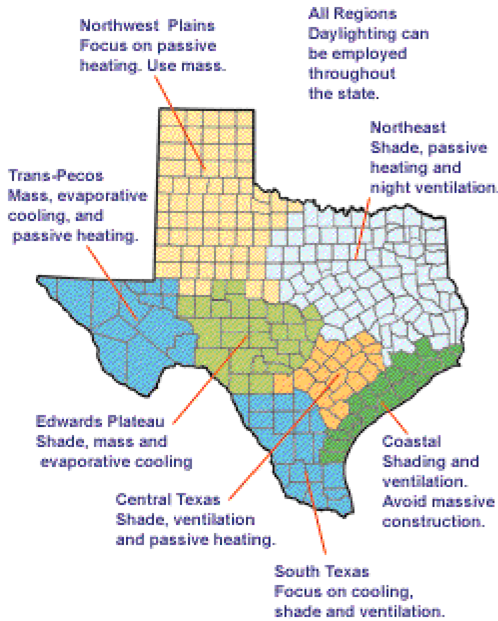

Figure 4: The Climate Regions of Texas. [8]

The Trinity River Basin

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What Can You Do to Combat Drought?

For communities and individuals to actively combat drought it often takes more than conserving water. Water planning is required too. For the best possible water planning water users should partake in the planning process, stay aware of drought conditions, partake in voluntary water conservation when needed, and inform water suppliers when there are water losses in the water system. [10]

Drought Plan-Community Involvement
According to the TCEQ's "A Drought Planning Guide for Public Water Systems in Texas" all water services must have a drought contingency plan. This plan lays out operations in case of extreme drought, periods of abnormally high water usage, supply contamination, or extended reduction in ability to supply water due to equipment failure. It is strongly suggested that the public be involved in the planning process. Typically water providers involve the public by forming citizen's advisory committees or task forces, holding public meetings, conducting surveys, seeking input directly from large-volume water customers (contractors, golf course operators, owners of car washes), or

distributing a draft plan for public review and comment prior to adoption. Taking part in these events allows local residents (who will be affected by the drought contingency plan) an input to the plan and a familiarization with the plan. [11] Figure 5 is a cartoon displaying the importance of being aware and prepared for drought conditions.

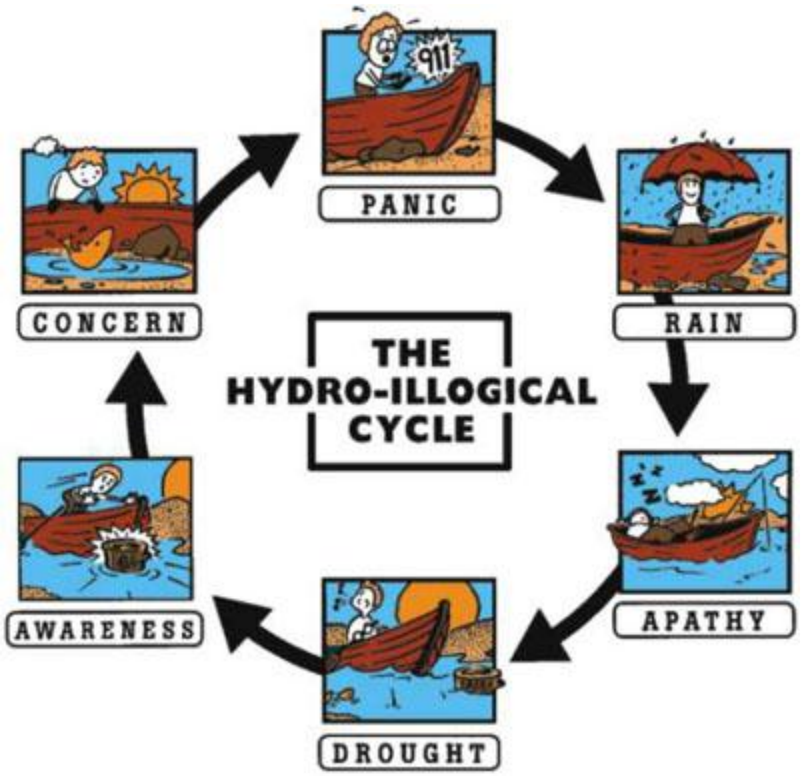

Figure 5: A cartoon from the Drought Mitigation Center to display the importance of being prepared for drought. [3]

Stay Informed About the State of Water Conditions

In the Trinity River Basin the Trinity River Basin Authority has jurisdiction over the definition of drought level. According to the Trinity River Basin Master Plan, each individual water supplier has a drought plan (including drought contingency triggers) for their system. It is the water suppliers' responsibility to inform customers of the level of drought. However, it is the public's social responsibility to ensure that they are informed and aware of the state of drought in their region. [9]

The IDIS website is one source of drought information. The IDIS allows users to sample climate data, hydrologic data, and drought indices to obtain a better understanding of drought. However, there are many sources of information available. The National Oceanic and Atmospheric Administration's Climate Prediction Center provides a "US Drought Assessment". This website provides seasonal drought predictions, drought data, experimental drought indicator blends, soil moisture data and precipitation and temperature data. The data available includes current data, as well as achieved historical data. [10] One of the links available on the "Drought Assessment" website is to the National Drought Monitor. The National Drought Monitor produces weekly images of drought severity for the United States, as can be seen in Figure 6. [13]

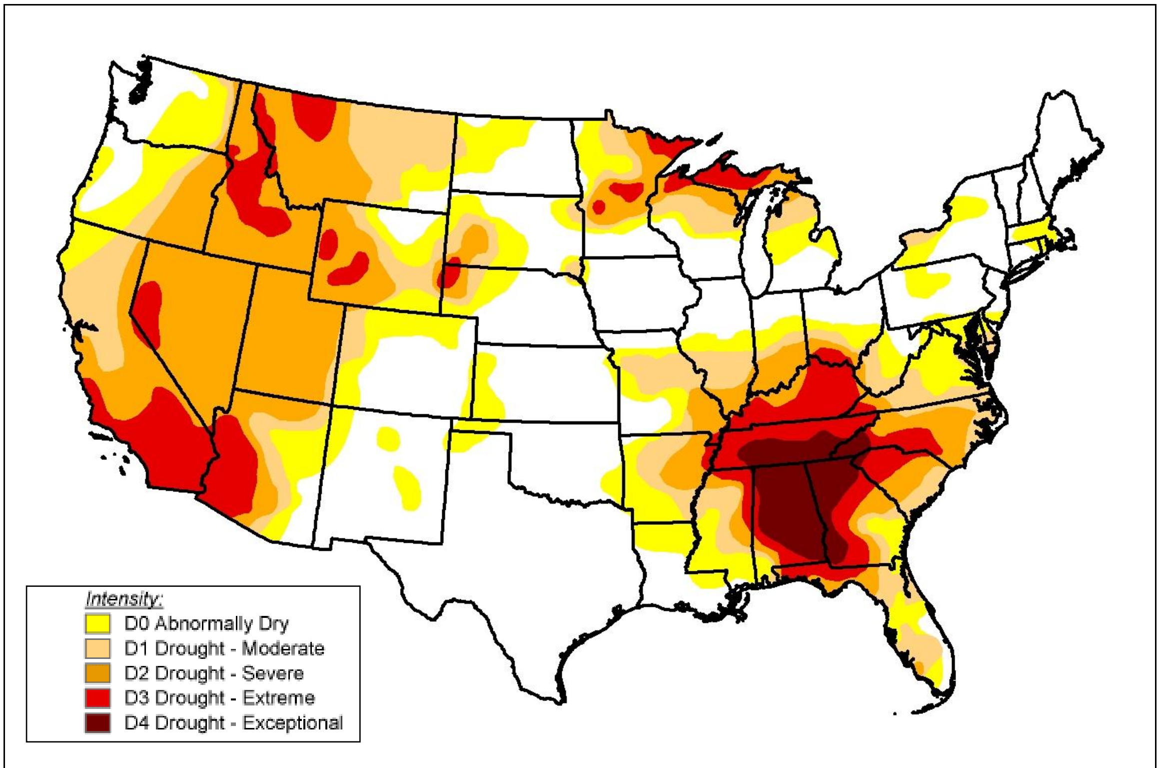

Figure 6: The US Drought Monitor for the week of August 28th, 2007[13]

The US Drought Monitor basis its drought severity on a blend of science. The maps are produced by the University of Nebraska-Lincoln in collaboration with several federal, state, academic and independent organizations. Links to this data are provided on the US Drought Monitor website, as well as, archived data. [13]

There are many drought resources available online. Some of the links can be found below in the Drought Links section of this report.

Voluntary Water Conservation

Water conservation is always important for a community to practice. Water is a valuable natural resource that should not be wasted. There are many things that can be done to conserve water. [10] Useful websites for tips and ideas about water conservation are:

Water Conservation Tips- http://www.monolake.org/socalwater/wctips.htm
The Water Conservation Portal- http://www.waterconserve.info/
Earth 911, Water Conservation- http://earth911.org/water/water-conservation/

Voluntary water conservation is typically part of a drought preparedness plan. For many drought plans, the early stages of drought call for voluntary conservation. TCEQ's "A Drought Planning Guide for Public Water Systems in Texas" establishes five levels of drought, based on the "The Texas Drought Preparedness Plan", that can be seen below in Table 2. [7]

Level of Drought Response	Type of Advisory	Typical Response to Advisory Level
1	Advisory	Raise public awareness of the supply situation and request voluntary reductions in nonessential water use
2	Watch	Implement mandatory restrictions on certain non essential water uses
3	Severe conditions	Implement ban on certain non-essential water uses and water rate surcharge for excessive use
4	Critical conditions	Continue ban on nonessential water uses, increase water rate surcharge, activate backup wells
5	Emergency conditions	Initiate emergency response procedures

Table 2: The TCEQ's Drought Planning Guide for Public Water Systems in Texas examples of drought response. [11]

For every water authority the definitions of these levels vary. For the Trinity River Authority (TRA) the level of drought is established by each individual water supplier. It is the water suppliers' responsibility to inform their water users when water restrictions are being enforced. Most of these conditions are based on percentage water availability for a given water system (see the Trinity River Basin Master Plan—2001, Drought Contingency Triggers). Responding to voluntary conservation can help mitigate the impacts of drought. [14]

Inform Water Supplier of Water Loss

One way to reduce water loss and improve water conservation is to report water loss to the water provider. [10] Some examples of water loss to report to the water provider are:

- Line leaks or breaks
- Leaky valves
- Water meters that don't work correctly
- Leaky fire hydrants

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Drought Links

National Drought Mitigation Center: www.drougth.unl.edu
NOAA Drought Information Center: http://www.drought.noaa.gov/
US Drought Monitor: http://drought.unl.edu/dm/monitor.html
Climate Prediction Center (CPC) US Drought Assessment:
http://www.cpc.ncep.noaa.gov/products/expert_assessment/drought_assessment.shtml
NOAA Climate Program Office-Intergovernmental Panel on Climate Change:
http://www.cpo.noaa.gov/ipcc/water_drought.html

Drought Education for Kids: www.drought.unl.edu/kids

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References

1. "North American Drought: a Paleo Perspective." 28 Aug. 2007. National Oceanic and Atmospheric Administration. 28 Aug. 2007 <http://www.ncdc.noaa.gov/paleo/drought/drght_what.html>.

2. "Drought." Wikipedia. 27 Aug. 2007 <http://en.wikipedia.org/wiki/Drought>.

3. "The National Drought Mitigation Center." 2007. The University of Nebraska - Lincoln. 27 Aug. 2007 <www.drought.unl.edu>.

4. "EL NIÑO EXPECTED TO INFLUENCE CENTRAL U.S. WINTER WEATHER." National Oceanic and Atmospheric Administration. 31 Oct. 2002. 30 Aug. 2007 <http://www.noaanews.noaa.gov/stories/s1059.htm>.

5. Byrns, Steve. "Is the Drought Over?" Ag News: News and Public Affairs 07 July 2005. 28 Aug. 2007 <http://agnews.tamu.edu/dailynews/stories/DRGHT/Jul0705a.htm>.

6. "Drought Information Center." 08 June-July 2007. National Oceanic and Atmospheric Administration. 27 Aug. 2007 http://www.drought.noaa.gov/.

7. State Drought Preparedness Plan. Drought Preparedness Council. Austin, TX: Governor's Division of Emergency Management, Texas Department of Public Safety, 2005. 1-42.

8. "Texas Renewable Energy Resources." Texas State Energy Conservation Office. 10 Sept. 2007 <www.infinitepower.org/resbuilding.htm>.

9. Trinity River Basin Master Plan. Trinity River Authority of Texas. 2007. 1-48.

10. "Drought and Public Water." Texas Commission on Environmental Quality. 27 Aug. 2007. 27 Aug. 2007 <http://www.tceq.state.tx.us/nav/util_water/drought.html>.

11. A Drought Planning Guide for Public Water Systems in Texas. Water Permits and Resource Management Div., Texas Commission on Environmental Equality. Austin, TX: Texas Natural Resource Conservation Commission, 2001.

12. "US Drought Assessment." Climate Prediction Center (CPC) Drought. 2007. Climate Prediction Center (CPC). 27 Aug. 2007 <http://www.cpc.ncep.noaa.gov/products/expert_assessment/drought_assessment.shtml>.

13. "US Drought Monitor." 22 Aug.-Sept. 2007. University of Nebraska - Lincoln. 27 Aug. 2007 <http://drought.unl.edu/dm/monitor.html>.

14. Trinity River Basin Master Plan. Trinity River Authority of Texas. 2001. 1-35.

15. "Water Balance." Wikipedia. Apr. 2007. 27 Aug. 2007 <http://en.wikipedia.org/wiki/Water_balance>.

16. "Water Science for Schools: the Water Cycle." USGS. 17 Aug. 2007. 27 Aug. 2007 <http://ga.water.usgs.gov/edu/watercycle.html>.

17. Drought Assistance Reference Guide for State Agencies. Dept. of Public Safety, the State of Texas. Austin, TX: Division of Emergency Management. 1-27.

What Are the Different Types of Drought?

There are three main types of drought: meteorological, agricultural, and hydrological. The first of these to occur is the meteorological drought. This occurs directly from climate variation. The results of the meteorological drought lead to an agricultural drought. A decrease in the availability of water causes soil moisture to decrease and vegetation stress to increase. This in turn leads to a hydrological drought. During a hydrological drought the effects of drought can be seen on the surface water. These three types of drought are discussed in further detail below. [3]

1. Meteorological drought is brought about when there is a prolonged period with less than average precipitation. Meteorological drought usually precedes the other kinds of drought.
2. Agricultural droughts are droughts that affect crop production or the ecology of the range. This condition can also arise independently from any change in precipitation levels when soil conditions and erosion triggered by poorly planned agricultural endeavors cause a shortfall in water available to the crops. However, in a traditional drought, it is caused by an extended period of below average precipitation.
3. Hydrological drought is brought about when the water reserves available in sources such as aquifers, lakes and reservoirs falls below the statistical average. Like an agricultural drought, this can be triggered by more than just a loss of rainfall. For instance, Kazakhstan was recently awarded a large amount of money by the World Bank to restore water that had been diverted to other nations from the Aral Sea under Soviet rule. Similar circumstances also place their largest lake, Balkhash, at risk of completely drying out.

The way these types of droughts occur can be seen below. Figure 7 shows the process in which the types of droughts occur and what occurs during these droughts. [3]

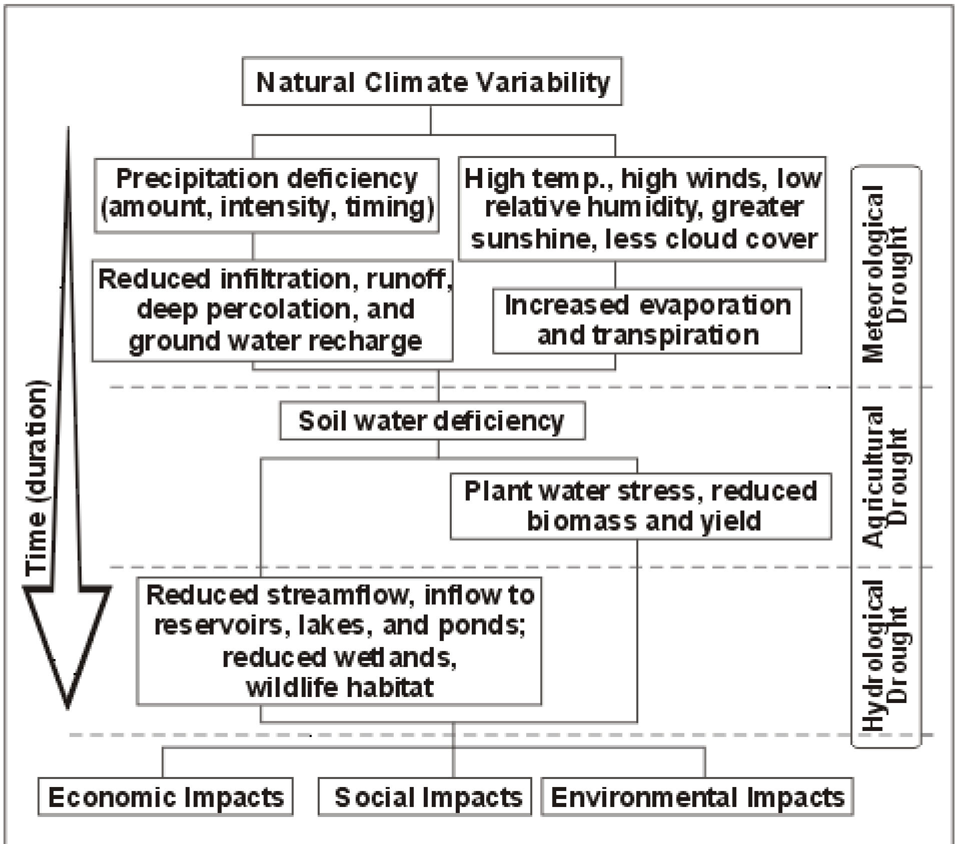

Figure 7: Types of drought through time. [3]

What is the Water Balance?

The water balance is an equation that accounts for the inputs and outputs of a water system. The water balance can describe a water system that ranges in size from an agricultural field or forest, to a river basin, to the entire earth's surface. Typical inputs to a water balance are precipitation and inflow. Typical outputs for a water balance are evaporation, evaportranspiration, soil infiltration and outflow. An additional variable factoring into a water balance is the change in storage within the water system. Water balances help to manage water supply and predict where water shortages/surpluses will be. [15]

How Does Water Cycle?

The earth's water is always in action. The relationship between the ocean, atmosphere and climate drives the water cycle. Starting with water being stored in the ocean, water is evaporated and enters the atmosphere. Once in the atmosphere the water vapor goes through condensation. The water is stored in the atmosphere until it is released to the earth in the form of precipitation. Some of the precipitation will be stored as ice and snow. Rainwater and snowmelt runs off the slopes to infiltrate groundwater or streams. Some of the water on the surface re-enters the atmosphere through evapotranspiration and evaporation. Water in the streams may be stored in reservoirs or lakes until re-entering the ocean. Water in the groundwater system is stored in aquifers until it enters the surface water system through springs or discharges directly into the ocean. A visual image of this can been seen in Figure 8. [16]

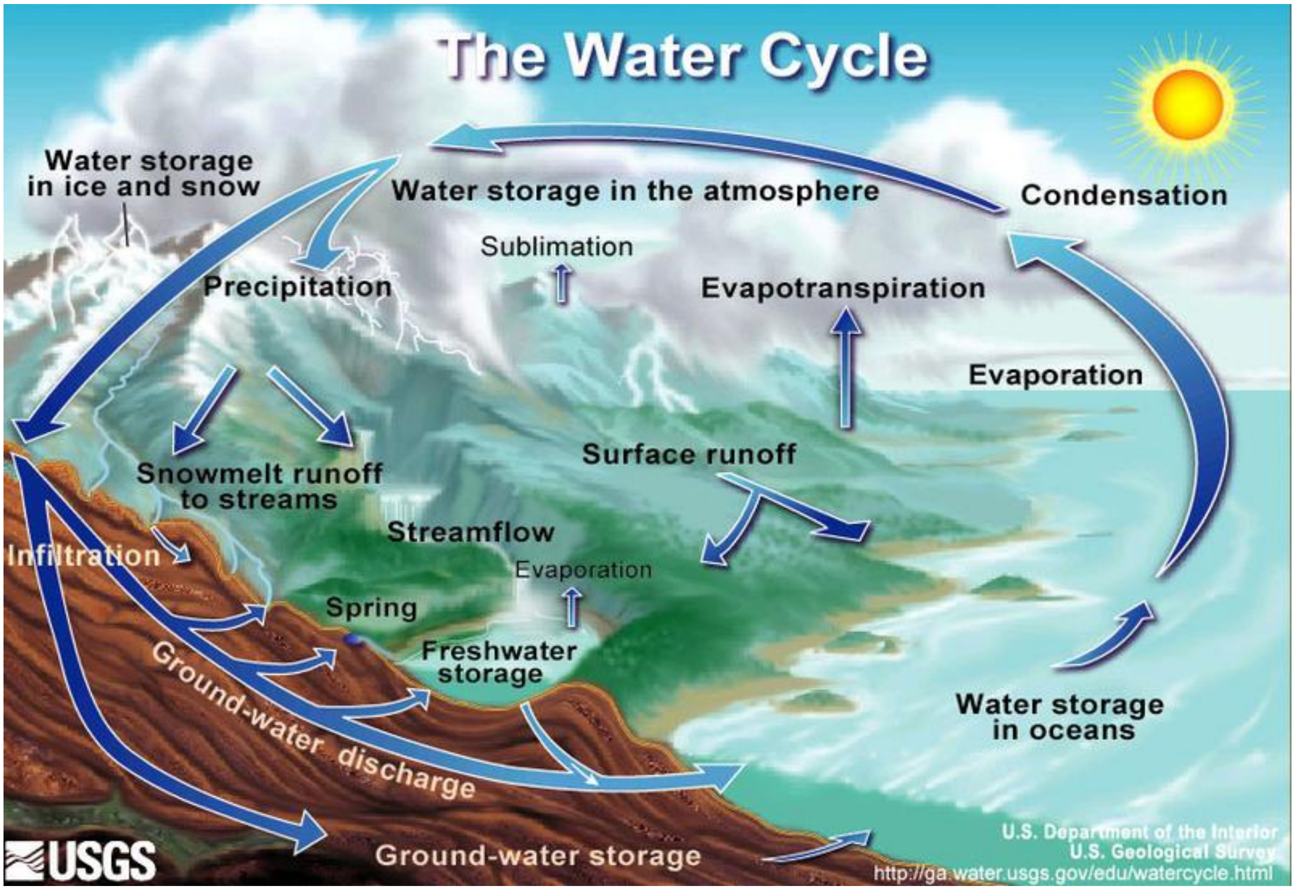

Figure 8: The water cycle. [16]

The Trinity River Basin

The Trinity River is a vast and expansive river. The Trinity River watershed contains 17965 square miles (about 6% of Texas's surface area). The Trinity River itself is 715 miles long. Because the basin is so large land types, soil type and climate vary greatly across the state. The northern portion of the watershed is covered by central Texas prairies. The dry climate of the northern portion receives only 29 inches of precipitation annually. As the river runs southeast the landscape changes from central Texas prairies, to piney woods, to Gulf Coastal prairies (which receive 53 inches of precipitation a year). Figure 9 shows the Trinity River Basin with existing reservoirs. [9]

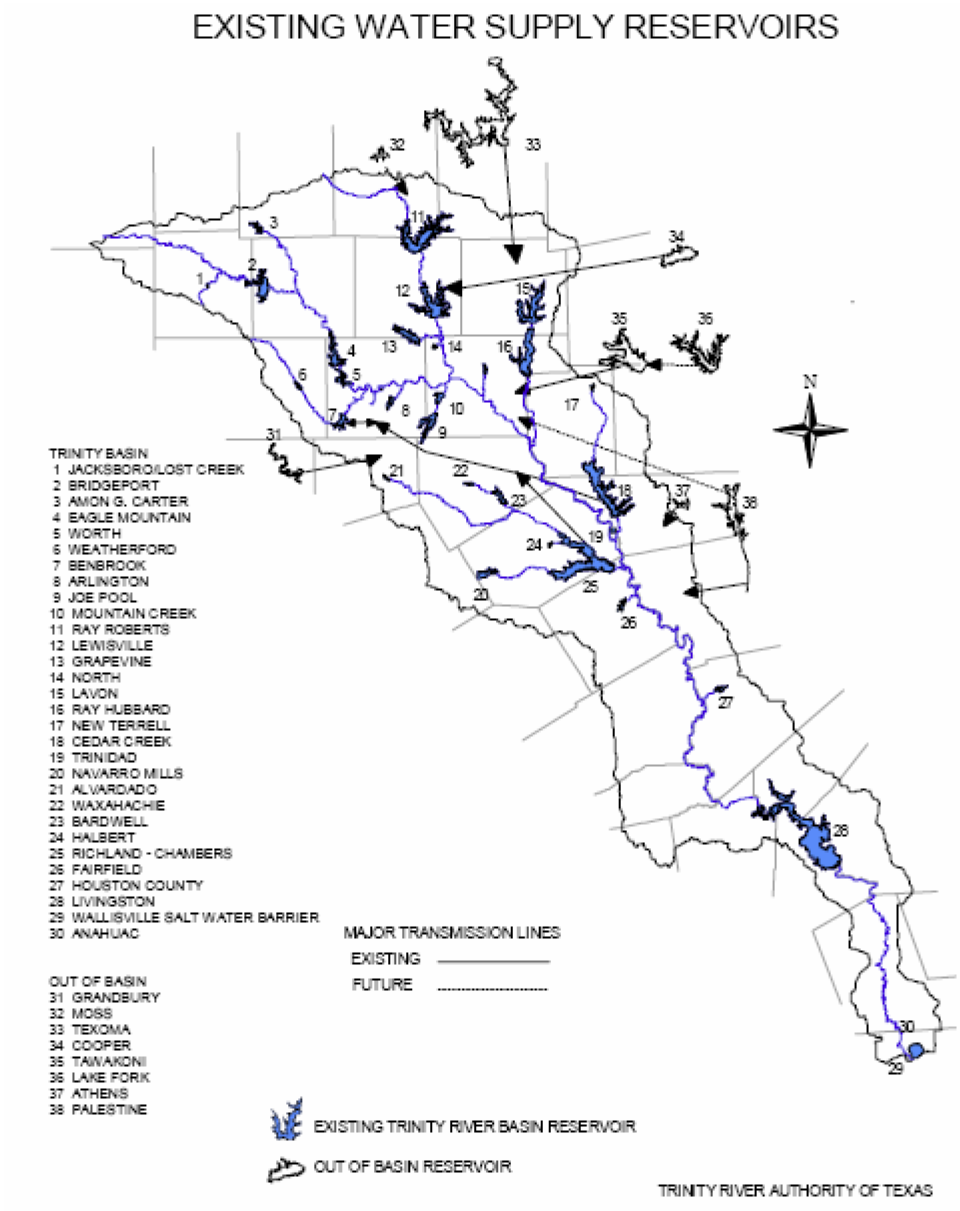

Figure 9: The Trinity River Basin with existing reservoirs. [9]

The river is the most developed watershed in the state. It contains more than 29 reservoirs, and is a primary source of water for around ten million people. The reservoir serves the Dallas/Fortworth Metroplex and parts of Houston. The reservoirs of the basin hold more than 5000 acre-feet of water in storage. In 1955 the Trinity River Authority (TRA) was created. The TRA includes all or part of 17 counties (containing twenty percent of the state's population) along the river basin. Although the watershed falls into water management regions C and H (as well as small portions of D, G and I), the TRA has been allotted much jurisdiction over the Trinity River Basin by House Bill 20. The basin as well as the water management districts can be seen below in Figure 10. [9]

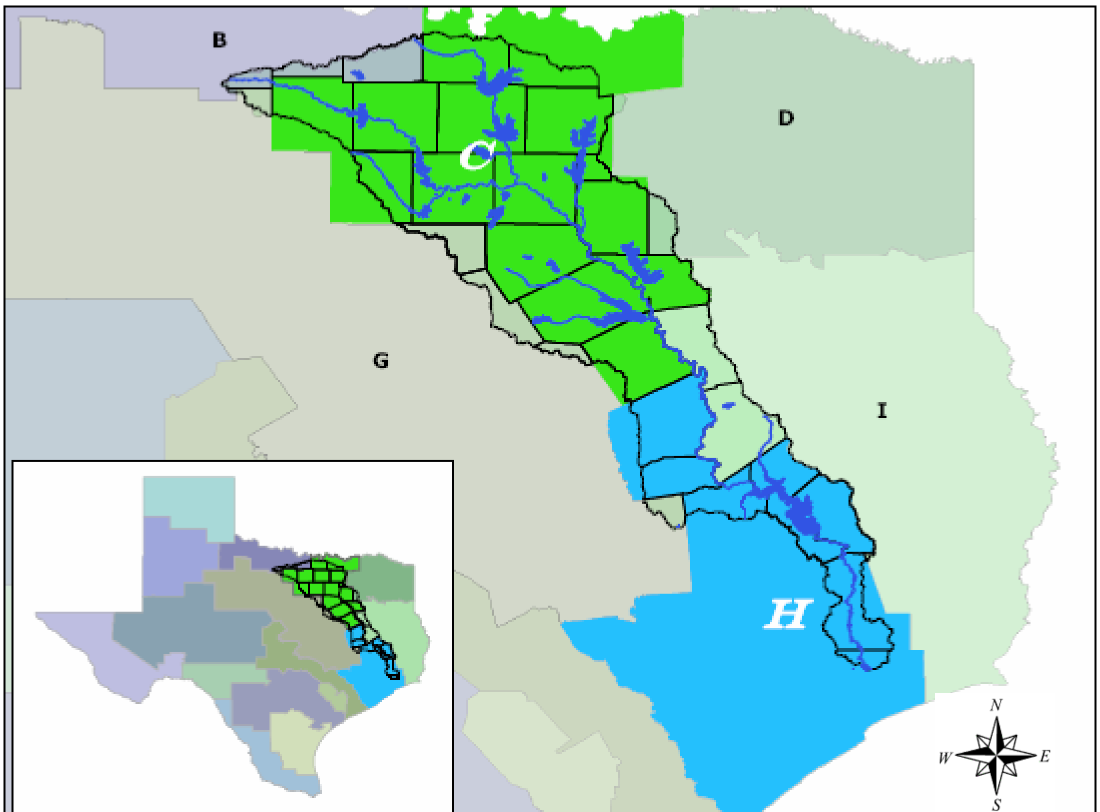

Figure 10: The Trinity River Basin and Texas Water Management Districts. [7]

Additionally the Trinity River Basin spans over three major aquifers (Carrizo, Gulf Coast, and Trinity) and five minor aquifers (Nacatoch, Queen City, Sparta, Woodbine, Yegua Jackson). These aquifers in relation to the basin can be seen below in Figure 11. [9]

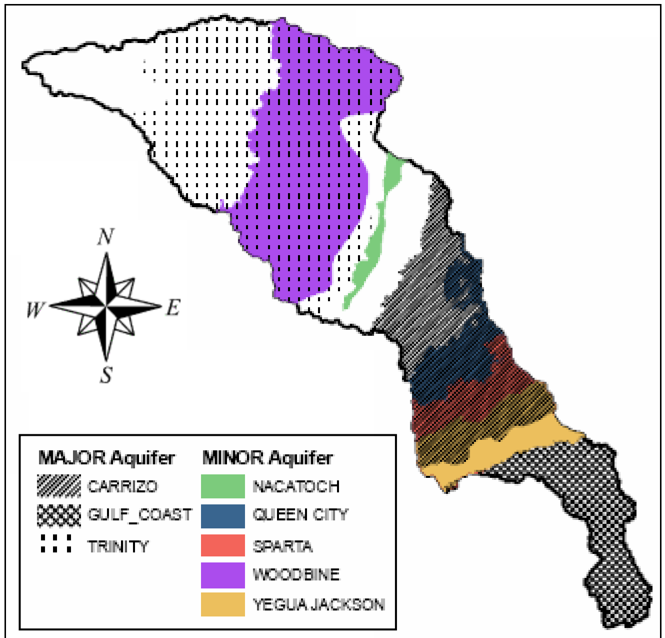

Figure 11: Aquifers of the Trinity River Basin. [9]

Assistance to Drought-Impacted Areas

Texas Water Development Board Drought Resource Contacts and Summary

The Texas Water Development Board (TWDB) is the state agency charged with statewide water resources planning and administration of low-cost financial assistance programs for the planning, design, and construction of water supply, wastewater treatment, flood control, and agricultural water conservation projects. TWDB has a variety of programs, services, and capabilities for assisting communities in developing and implementing local responses to drought-induced water supply problems. This includes: drought related information on drought indices, water supply reservoir contents, groundwater levels, etc.; technical assistance with local drought management planning and water conservation practices; provision of information and technical assistance for the identification of alternative water sources; and providing low-cost financial assistance for the development of alternative water sources. [17]

Agency Contacts for Assistance

Type of Assistance	Name	Telephone	E-mail
Media Contact	Carla Daws	512-463-7956	Carla.Daws@twdb.state.tx.us
Municipal & Industrial Drought Management and Conservation	John Sutton	512-463-7988	John.Sutton@twdb.state.tx.us
Agricultural Drought Management and Conservation:	Mark Michon	512-463-7984	Mark.Michon@twdb.state.tx.us
Drought Indices and Water Resources Data:	Robert Bradley	512-936-0870	Robert.Bradley@twdb.state.tx.us
Water Audit and Leak Detection:	Mark Mathis	512-463-0987	mark.mathis@twdb.state.tx.us
Water Conservation Public Information-English & Spanish:	Patsy Waters	512-463-7955	Patsy.Waters@twdb.state.tx.us
Planning Data request for the state of Texas:	Wendy Barron	512-936-0886	wendy.barron@twdb.state.tx.us
Financial Assistance for Water Supply Improvements for Border and Non-Border Areas:	Jeff Walker	512-463-7779	jeff.walker@twdb.state.tx.us

Weblink: http://www.twdb.state.tx.us/data/drought/Contacts.asp

Bibliography

1. "North American Drought: a Paleo Perspective." 28 Aug. 2007. National Oceanic and Atmospheric Administration. 28 Aug. 2007 <http://www.ncdc.noaa.gov/paleo/drought/drght_what.html>.

2. "Drought." Wikipedia. 27 Aug. 2007 <http://en.wikipedia.org/wiki/Drought>.

3. "The National Drought Mitigation Center." 2007. The University of Nebraska - Lincoln. 27 Aug. 2007 <www.drought.unl.edu>.

4. "Water Balance." Wikipedia. Apr. 2007. 27 Aug. 2007 <http://en.wikipedia.org/wiki/Water_balance>.

5. Wu, Hong, and Donald Whilhite. "An Operational Agricultural Drought Risk Assessment Model for Nebraska, USA." Natural Hazards 33 (2004): 1-21.

6. Whilhite, Donald A., and Mark D. Svoboda. "Understanding the Complex Impacts of Drought: a Key to Enhancing Drought Mitigation and Preparedness." Water Resource Management 21 (2007): 763-774.

7. "Water Science for Schools: the Water Cycle." USGS. 17 Aug. 2007. 27 Aug. 2007 <http://ga.water.usgs.gov/edu/watercycle.html>.

8. Maidment, David R. Arc Hydro: GIS for Water Resources. 1st ed. Redlands, CA: ESRI P, 2002. 141-166.

9. IPCC 4th Assessment Report: Working Group I Report "Physical Science Basis" Intergovernmental Panel on Climate Change. New York, NY: Cambridge UP, 2007. 254-265.

10. State Drought Preparedness Plan. Drought Preparedness Council. Austin, TX: Governor's Division of Emergency Management, Texas Department of Public Safety, 2005. 1-42.

11. "Historical Graphs of the Palmer Index." What is Drought? 2006. National Drought Mitigation Center. 31 Mar. 2008 <http://www.drought.unl.edu/whatis/palmer/txgulf.gif>.

12. "20th Century Drought." Drought: a Paleo Perspective. 27 Mar. 2008 <http://www.ncdc.noaa.gov/paleo/drought/drght_history.html>.

13. "What Happens in a Drought?" LCRA. 19 Sept. 2007. <http://www.lcra.org/water/supply/drought.html>.

14. Whilhite, D.A. 1990. Planning for drought: A process for state government. IDIC Technical Report Series 90-1. International drought Information Center, University of Nebraska-Lincoln.

15. Ray Motha, Recommendations on Drought Monitoring by the U.S. National Drought Policy Commission, U. S. Department of Agriculture, Washington, DC, U.S.A

16. "Texas Renewable Energy." Renewable Energy: the Infinite Power of Texas. 31 Mar. 2008 <www.infinitepower.org/resbuilding.htm>.

17. Booth, D., et al. (2004), Web Services Architecture, *WC3 Working Group Note*, 98.

18. A Drought Planning Guide for Public Water Systems in Texas. Water Permits and Resource Management Div., Texas Commission on Environmental Equality. Austin, TX: Texas Natural Resource Conservation Commission, 2001.

19. NIDIS Program Implementation Team. The National Integrated Drought Information System Implementation Plan. National Oceanic and Atmospheric Administration and the National Drought Mitigation Center. NIDIS Program Office, 2007. 1-28.

20. Drought Monitoring and Early Warning: Concepts, Progress and Future Challenges. World Meteorological Organization. World Meteorological Organization, 2006. 1-26.

21. "North American Drought Monitor." NOAA Satellite and Information Service. 11 Apr. 2008. National Oceanic and Atmospheric Administration. 31 Mar. 2008 <http://www.ncdc.noaa.gov/oa/climate/monitoring/drought/nadm/>.

22. "NHDPlus Home." National Hydrography Dataset Plus. 24 Mar. 2008. Horizon Systems. 28 Mar. 2008 <http://www.horizon-systems.com/nhdplus/>.

23. "Reservoir Volumetric Surveys." 16 July 2004. Texas Water Development Board. 11 Jan. 2008 <http://www.twdb.state.tx.us/assistance/lakesurveys/volumetricindex.asp>.

24. Messinger et al. "North American Regional Reanalysis." Bulletin of the American Meteorological Society (2005): 1-42.

25. "US Drought Assessment." National Climate Prediction Center. 10 Apr. 2006. National Oceanic and Atmospheric Administration. 11 Jan. 2008 <http://www.cpc.ncep.noaa.gov/products/expert_assessment/drought_assessment.shtml>.

26. "Water Watch." Maps of Real-Time Streamflow Compared to Historical Streamflow for the Day of the Year (Texas. 31 Mar. 2007. USGS. 31 Mar. 2007 <http://water.usgs.gov/waterwatch/?m=real&w=map&r=tx>.

27. "National Water Information System." Web Interface. 11 Jan. 2008. US Geological Survey. 11 Jan. 2008 <http://waterdata.usgs.gov/nwis>.

28. Dracup, J A. "Drought Monitoring." Stochastic Hydrology and Hydraulics 5 (1991): 261-266.

29. "Drought Impact Reporter." University of Nebraska - Lincoln. 11 Jan. 2008 <http://droughtreporter.unl.edu/>.

30. "Drought Monitoring." Climate Prediction Center. 11 Apr. 2008. National Weather Service. 25 Mar. 2008 <http://www.cpc.noaa.gov/products/monitoring_and_data/drought.shtml>.

31. "NetCDF." Wikipedia. 12 Feb. 2008. 31 Mar. 2008 <http://en.wikipedia.org/wiki/NetCDF>.

32. Jantzen, T.L. (2007). “Implementation of a State Hydrologic Information System.” Report, The University of Texas at Austin.

33. Whiteaker, T., et al. (2006), CUAHSI Web Services Workbook, 91 pp, CUAHSI . <http://www.cuahsi.org/his/docs/HIS-workbook-20061130.pdf>

34. Trinity River Basin Master Plan. Trinity River Authority of Texas. 2007. 1-48

Vita

Virginia Burton Smith is the daughter of Patricia and Roger Smith. She was born in Keflavik, Iceland October 8th, 1981. Virginia attended primary school in Germany, Alabama, Arizona, Oklahoma, Japan, Virginia, Greece and Georgia. She graduated from Brookwood High School in Lawrenceville, Georgia in 1999. In the fall of 1999 Virginia began attending the Georgia Institute of Technology (GA Tech), in Atlanta, Georgia. In 2003 she graduated with a Bachelors of Science in Civil and Environmental Engineering. While attending GA Tech Virginia lettered in track and cross country, was an active member of the American Society of Civil Engineering, served as an officer in Alpha Xi Delta sorority, and volunteered in community building groups team buzz and the Atlanta Children's Shelter. She also worked as a co-op for Lowe Engineers, in Atlanta, Georgia. Upon graduating from GA Tech Virginia briefly took a job as an EIT at Lowe Engineers before joining the Peace Corps. In the spring of 2004 Virginia moved to Samoa to serve as a Peace Corps volunteer. She worked for the Peace for two years on the Samoan National Water Project and various small scale development projects. In the summer of 2006 Virginia returned to the United States and began graduate school at the University of Texas in Austin.

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This report was typed by the author.